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THE STUDY OF ACCESSORY MINERALS IN IGNEOUS AND METAMORPHIC ROCKS*

JOHN C. REED, *U. S. Geological Survey*

INTRODUCTION

The constantly increasing interest of geologists during the last 25 years in the study of accessory minerals in igneous and metamorphic rocks, and in the distribution of these minerals in sediments led to the formation, in 1931, of a Committee on Accessory Minerals of Crystalline Rocks in the Division of Geology and Geography of the National Research Council. Much of the work in this general field has been done by British scientists, but in recent years, in part because of the application of results to oil-field problems, the work of others along this line has been stimulated.

Winchell,[1] in the first report of the committee, defined its field as "a study of the nature of the accessory minerals of crystalline rocks, their variation in time and space in igneous bodies and metamorphosed masses, and their distribution in sediments."

The present paper traces the development of the study of accessory minerals in igneous and metamorphic rocks, and of the application of such study to broader problems of igneous geology, such as correlation of, or differentiation between, igneous masses. The paper is based largely on the abstracts of the literature that have been prepared by the various members of the committee, as the first stage of the committee's work. The phase of the subject having to do with the distribution of the accessory minerals in sediments is not considered here.

DEFINITION OF ACCESSORY MINERAL

Any worker in the field of accessory minerals in igneous and metamorphic rocks soon discovers that the term "accessory mineral" has a variety of meanings, the meaning in any particular paper depending on the writer who is using it. When the study of these minerals is set aside as a particular field of activity, it is apparent that either there must be some unanimity of usage of the principal term involved, or else each writer must define his usage.

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[1] Winchell, A. N., and others, Accessory minerals of crystalline rocks: *Nat. Research Council, Bull.* **89**, p. 142, 1932.

According to Webster's dictionary,[2] "accessory" used as an adjective modifying things means "accompanying as a subordinate; aiding or contributing in a secondary way; connected as an incident or subordinate to a principal; additional," and "accessory mineral" is defined as "any mineral not regarded as an essential constituent of a particular rock, although it may be frequently, or even usually, present."

Holmes' similar definition[3] is "a term applied to minerals occurring in small quantities in a rock, whose presence or absence does not affect its diagnosis."

La Forge's definition[4] is practically identical, being "those mineral constituents of a rock that occur in such small amounts that they are disregarded in its classification and definition. Opposed to essential minerals."

Osann[5] divides the rock minerals into three main groups—the essential or major constituents (*Wesentlichegemengteile* or *Hauptgemengteile*), the minor constituents (*Nebengemengteile*), and the subordinate or excess constituents (*Akzessorischegemengteile* or *Übergemengteile*).

The *Nebengemengteile* include such minerals as apatite, iron ores, and zircon. They are present in most rocks but are not used in naming the rock and are not essential to the rock. The *Übergemengteile* are further subdivided into vicarious or substituted subordinate constituents (*vikariierende*), characteristic subordinate constituents (*charakteristischen*), and accidental or fortuitous subordinate constituents (*zufällige*). The first subgroup includes such minerals as tourmaline in place of mica in granite, or haüynite in place of nepheline in tephrite. The second embraces such minerals as titanite in granite, pyrope in serpentine, or perovskite in melilite basalt. Examples of the minerals of the third subgroup are fluorite in granite, galena in sandstone, and sphalerite in limestone.

Johannsen[6] classifies the mineral constituents of igneous rocks as follows:

- "Primary—
  - Essential or chief constituents
  - Accessory—
    - Minor accessories
    - Auxiliary minerals
- Secondary constituents—Caused by
  - Addition of material
  - Replacement
  - Weathering

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[2] Webster's new international dictionary of the English language, 1931.

[3] Holmes, Arthur, *The nomenclature of petrology*, p. 23, London, Thos. Murby & Co., **1920.**

[4] Fay, A. H., A glossary of the mining and mineral industry: *U. S. Bur. Mines, Bull.* **95,** p. 13, 1920.

[5] Osann, A., *Elemente der Gesteinslehre*, H. Rosenbusch, pp. 17–18, Stuttgart, **1923.**

[6] Johannsen, Albert, *A descriptive petrography of the igneous rocks*, p. 28, Univ. Chicago Press, **1931.**

Included (foreign) constituents—— { May be rock fragments or minerals

"The primary constituents were formed during the solidification of the rock. Of these, the essentials are those which, by definition, are necessary to the rock. The accessory constituents embrace the minor accessories and the auxiliary minerals. The former include small amounts of the minerals usually present, such as apatite, zircon, titanite, the iron ores, etc., whose absence or presence does not change the classification of the specimen. In some cases the accessory minerals are of unusual interest or they have become so prominent that they are conspicuous—for example, titanite in syenite, or topaz or tourmaline in granite. Such minerals may be called auxiliary constituents. Secondary minerals may be introduced by the addition of material such as boron, fluorine, etc., to form tourmaline, topaz, fluorite, etc.; they may be formed by replacement, as kaolin, chlorite, epidote, amphibole, titanite, calcite, quartz, etc.; or by weathering, as calcite, limonite, and indeterminable hydrous aluminum silicates."

Wright,[7] in a paragraph on the classification and general features of accessories, notes the classifications used by Grantham and by Wells. Grantham[8] makes two divisions—primary or pyrogenic accessories, such as zircon, apatite, and fluorite; and secondary or infiltrated accessories, including such minerals as tourmaline, topaz, and some fluorite. Wells[9] classifies accessories of granites as normal (zircon, titanite, etc.), pneumatolytic (tourmaline, topaz), contamination (garnet, andalusite), and secondary (epidote, zoisite). One unfamiliar with the individual meanings given to terms would be confused to find that the "primary" accessories of one paper are the "normal" accessories of another, and that the "secondary" accessories of one author are pneumatolytic and of another hydrothermal.

Winchell,[10] as chairman of the Committee on Accessory Minerals of Crystalline Rocks, writes, "In the work of the committee and in research work related to it a serious question has arisen this year regarding the meaning of the term 'accessory minerals.' Five members of the committee are agreed in the following statements:

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[7] Wright, J. F., Accessory minerals in the study of granite batholiths: *Roy. Soc. Canada Trans.*, 3d ser., vol. **26**, sec. 4, pp. 253–254, 1932.

[8] Grantham, D. R., The petrology of the Shap granite: *Geol. Assoc. Proc.*, vol. **39**, pp. 304–307, 1928.

[9] Wells, A. K., The heavy-mineral correlation of intrusive igneous rocks: *Geol. Mag.*, vol. **68**, pp. 255–262, June 1931.

[10] Winchell, A. N., Report of the committee on accessory minerals of crystalline rocks for 1934–35: *Nat. Research Council, Div. Geology and Geography*, Ann. Rept., **1935**, Appendix F, p. 1, April 27, 1935.

"For the purposes of the committee, the 'accessory minerals' of rocks are those which are present in such small amounts that they are studied to the best advantage by methods involving concentration rather than by ordinary thin-section methods. Such minerals as quartz and even feldspar are occasionally found in very small amounts in certain igneous rocks. Nevertheless, they are not considered as accessory minerals, even in those rocks, because there is at present no known advantage to be derived from studying them by concentration methods.

"Accessory minerals should not be confused with the 'heavy minerals'; hornblende and biotite are examples of heavy minerals which are rare in some granites and are therefore often included among the accessory minerals. But, at least in most cases, it seems to be true that they can be studied to the best advantage by ordinary thin-section methods. Furthermore, experience has shown that if they are included in the studies made by concentration methods, they are likely to introduce difficulties quite out of proportion to any benefits derived from their study by these methods.

"Professor Tolman does not agree with these statements but states that the term 'accessory minerals' has a quite definite meaning and any redefinition may cause confusion. He thinks the purpose might be achieved simply by pointing out the group of minerals most suitable for study through concentration. He agrees that the inclusion of the ferromagnesian minerals may obscure the more significant relations of the more useful minerals, and, moreover, that they are best studied in thin section."

The report does not state which "definite" meaning of the term "accessory minerals" is adhered to by Professor Tolman. Presumably it is the more general one, as expressed by the dictionary, Holmes, or La Forge, and not either of the more restricted meanings as used by Osann or Johannsen.

The present writer now feels that the general rather inclusive meaning as worded by Holmes, namely, "a term applied to minerals occurring in small quantities in a rock, whose presence or absence does not affect its diagnosis," is the best. The definition has two distinct advantages. First, it applies to all rocks—igneous, metamorphic, and sedimentary. Secondly, its meaning is almost inflexible. The simple definite qualifications must be met: an accessory mineral must be present in small amount and its presence or absence must not affect the diagnosis of the enclosing rock. The only latitude in application lies in the interpretation of what percentages of a mineral constitute "small quantities." Perhaps the definition could be worded "occurring in quantities so small that they do not affect the diagnosis of the rock."

This definition is, of course, very broad, as it includes minerals formed by recrystallization, by hydrothermal activity, by pneumatolysis, and even by weathering. Under this usage of the term the accessory minerals may then be appropriately subdivided as required for a more specific meaning. One convenient basis of subdivision is suggested by the first sentence of this paragraph—namely, that of genesis. Another might be based on physical properties—for example, "heavy accessories" could be those whose specific gravity is greater than 2.86, the specific gravity of bromoform. A third could be based on chemical composition, thus giving a group such as "sulphide accessories."

According to such a classification most of the literature on accessories in igneous and metamorphic rocks that has been abstracted and studied by the committee has dealt with "primary heavy accessories," "pneumatolytic heavy accessories," and "hydrothermal heavy accessories."

The Development of the Study of Accessory Minerals of Igneous and Metamorphic Rocks

Most of the early and many of the recent papers on igneous and metamorphic rocks either entirely ignore the accessories or simply mention the species identified. Occasionally they were given more attention, and the following citations from those papers published prior to that of Rastall and Wilcockson[11] in 1915 will serve to illustrate early attempts to use the accessories in the study of igneous and metamorphic rocks.

As early as 1884 Thurach[12] noted the widespread distribution of zircon, rutile, anatase, and brookite. He described the crystallography of anatase and brookite, and came to the conclusions that anatase and brookite never occur in unaltered crystalline rock but are first developed at the time of replacement, that anatase and brookite have been formed in the sedimentary rocks and are found also in secondary ore deposits, that the pseudobrookite found in altered basalt and phonolite of the Kreuzberg stock in the Rhone Valley was formed during the weathering of the basalt and phonolite, and that in considering the derivation of the sedimentary rocks from the various rocks of the basement complex, staurolite, of all the minerals found in the sedimentary rocks, deserves special consideration.

Rastall and Wilcockson[13] cite two early papers of Khrushchov,[14] who attempted to determine what habits of zircon are characteristic of various igneous and metamorphic rocks.

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[11] Rastall, R. H., and Wilcockson, W. H., The accessory minerals of the granitic rocks of the English Lake district: *Geol. Soc. London Quart. Jour.*, vol. **71**, pp. 592–622, 1915.

[12] Thurach, Hans, Über das Vorkommen mikroskopischer Zirkone und Titanmineralien in den Gesteinen: *Physikal. med. Gesell. Wurzburg Verh.*, neue Folge, *Band* **18**, Nr. 10, pp. 1–82, 1884.

[13] Rastall, R. H., and Wilcockson, W. H., *op. cit.*, pp. 618–619.

[14] Khrushchov, K. D., Über holocrystalline makrovariolithische Gesteine: *Acad. Imp. Sci. St.-Pétersbourg Mém.*, ser. 7, vol. **42**, no. 3, 1894; Beitrag zur Kenntnis der Zirkone in Gesteinen: *Min. Pet. Mitt.*, neue Folge, *Band* **12**, p. 423, 1886.

In 1893 Keyes[15] stated that the primary nature of epidote in Maryland granites is indicated by its presence in fresh rocks, its occurrence as inclusions in sphene, its good crystal outline, and the presence in it of cracks containing biotite in optic orientation with surrounding biotite crystals. Almost contemporaneously, Hobbs[16] came to the same conclusions on similar evidence.

Trueman,[17] in 1912, pointed out that zircon may not always be formed as a pyrogenetic igneous rock mineral but may originate or be secondarily enlarged through the agency of water or gases emanating from intrusions. Two years later Winchell[18] used the presence of well-rounded zircon particles in schists of the Rabbit district, Montana, as evidence that the schists are of sedimentary origin because "nearly all zircon in igneous rocks and their metamorphic equivalents is clear and sharply angular."

Leith and Mead[19] made a more general statement the next year, when they said; "The separation of minute accessory constituents by washing is a means for identifying origin of schists and gneisses which has not yet been sufficiently used. Minerals of igneous rocks, like monazite, zircon, sphene, and garnet, are remarkably resistant to weathering and remain in well-defined crystals in the residual mantle when all the other constituents have altered. When transported they become worn and rounded and tend to segregate with sand rather than argillaceous sediments. In the schistose equivalent of the sand deposits the rounded grains persist, particularly the zircons, and afford evidence of sedimentary origin."

Later work has shown that the zircons of many igneous rocks are well rounded by resorption. The work of Rastall and Wilcockson[20] on the rocks of the English Lake district was the most comprehensive study of the accessories of a suite of igneous rocks that had been attempted to 1915. This paper marked the beginning of a new phase of studies of this type. Their earlier studies of accessories of igneous rocks in connection with investigations of the origin of certain minerals in sediments led them to undertake the examination of a well-defined group of igneous rocks. The rocks of the Lake district were selected because material was available, the district includes several intrusive bodies that have variations within themselves and that have numerous apophyses with a considerable range in rock type, and the geologic relations and petrographic character of the rocks were well known.

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[15] Keyes, C. R., Epidote as a primary component of eruptive rocks: *Geol. Soc. Am. Bull.*, vol. **4**, pp. 305–312, 1893.

[16] Hobbs, W. H., New occurrence of parallel intergrowths of the minerals allanite and epidote: *Am. Geologist*, vol. **12**, pp. 218–219, 1893.

[17] Trueman, J. D., The value of certain criteria for the determination of the origin of foliated crystalline rocks: *Jour. Geology*, vol. **20**, p. 248, 1912.

[18] Winchell, A. N., Mining districts of the Dillon quadrangle, Montana, and adjacent areas: *U. S. Geol. Survey, Bull.* **574**, p. 128, 1914.

[19] Leith, C. K., and Mead, W. J., *Metamorphic geology*, p. 225, New York, Henry Holt & Co., **1915.**

[20] Rastall, R. H., and Wilcockson, W. H., *op cit.*, pp. 592–622.

These authors say: "The accessory minerals of the rocks examined show very wide variations. Nevertheless, when the results for each intrusion are taken separately, there is evidence of a distinct similarity running through all varieties. . . . On the whole, the rarer constituents of each intrusion show a fairly constant distribution, but this resemblance does not always extend to the apophyses. . . . The general results of this work, when compared with the published descriptions, show that enumerations of accessory minerals founded on the examination of rock sections alone are quite inadequate and often misleading. . . . The whole procedure is so simple and rapid that it might well be applied to all investigations of igneous rocks, as a check on the results obtained from rock sections alone."

The next stage in the development of studies of accessory minerals is marked by a group of papers by Brammal and Harwood,[21] who studied the petrology of the Dartmoor granite, with emphasis on the accessories. In their third paper cited here they use the term "index figure," which is defined as the average percentage by weight of mineral grains of specific gravity greater than 2.86 obtainable from crushed rock material that has been washed free from rock flour. This term has since come into more or less general usage.

Milner[22] points out the value of such work as that of Brammal and

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[21] Brammal, Alfred, and Harwood, H. F., The occurrence of rutile, brookite, and anatase on Dartmoor: *Mineralog. Mag.*, vol. **20**, pp. 20–26, 1923; Occurrences of zircon in the Dartmoor granite: *Idem*, vol. **20**, pp. 27–31; The Dartmoor granite—its mineralogy, structure, and petrology: *Idem*, vol. **20**, pp. 39–53; The occurrence of a gold-bearing pegmatite on Dartmoor: *Idem*, vol. **20**, pp. 201–211, 1924; Tourmalinization in the Dartmoor granite: *Idem*, vol. **20**, pp. 319–330, 1925.

Brammal, Alfred, The Dartmoor granite: *Geol. Assoc. London Proc.*, vol. **37**, pp. 251–277, 1926; Gold and silver in the Dartmoor granite: *Mineralog. Mag.*, vol. **21**, pp. 14–20, 1926.

Brammal, Alfred, and Harwood, H. F., The temperature range of formation for tourmaline, rutile, brookite, and anatase in the Dartmoor granite: *Mineralog. Mag.*, vol. **21**, pp. 205–220, 1927.

Brammal, Alfred, Dartmoor detritals—A study in provenance: *Geol. Assoc. London Proc.*, vol. **39**, pp. 27–48, 1928.

[22] Milner, H. B., *Sedimentary petrography*, pp. 408, 409, London, Thomas Murby & Co., **1929.**

Harwood: "The work on the Dartmoor granite has yielded abundant evidence of the value attaching to an intensive study of such accessory minerals. It has shown the existence of a rich and varied collection of species, many of which were previously not known to occur in that rock; it has stressed and proved conclusively the significance of varietal characters of these minerals and has thus been the direct means of focusing attention on mineral vagaries so often passed by as adventitious or unimportant. The wider investigations, combining both field and laboratory observations, have shown that particular accessory mineral assemblages may be characteristic of certain stages of intrusion or consolidation, or of specific developments and modifications of the normal rock, thus materially aiding correlation or differentiation of types. Their potentiality extends also to geochemical data, with which petrogenic problems are intimately bound up. Thus has a new scope of inquiry been instituted, a comprehensive technique established, which neither igneous nor sedimentary petrologists can afford to ignore."

In 1927 Groves[23] published the first two of several papers that deal principally with the study of the accessories of intrusive igneous rocks. He concludes that correlation of isolated plutonic outcrops by means of the accessories is very satisfactory for the whole area of the Channel Islands and that it demands further recognition. He says that it is quicker than chemical analysis and has the advantage that the crystallization history is also revealed. He points out that zircon and apatite are perhaps the minerals whose characters are likely to be the most useful for correlation and stresses the importance of varietal characters and "index figure."

Groves in his paper on the correlations of the granites of Brittany, the Channel Islands, and the Cotentin holds that, at least in these examples, neighboring granites, particularly masses injected along a common tectonic axis, reflect their relationships in possessing heavy mineral suites with many points in common, and this because such minerals as zircon, apatite, monazite, rutile, iron ores, and sphene generally crystallize from the magma at an early stage of the cooling and thus, in their color, inclusions, habits, and peculiarities, exhibit marked characteristics dependent on the original composition and early cooling history.

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[23] Groves, A. W., The heavy minerals of the plutonic rocks of the Channel Islands—1, Jersey: *Geol. Mag.*, vol. **64**, pp. 241–251, 1927; The heavy minerals of the plutonic rocks of the Channel Islands—2, Guernsey, Sark, and Alderney: *Idem*, pp. 457–473; The identification of dumortierite as grains; dumortierite in Cornish granites: *Mineralog. Mag.*, vol. **21**, pp. 489–492, 1928.

Groves, A. W., and Mourant, A. E., Inclusions in the apatites of some igneous rocks: *Mineralog, Mag.*, vol. **22**, pp. 92–99, 1929.

Groves, A. W., The heavy mineral suites and correlations of the granites of northern Brittany, the Channel Islands, and the Cotentin: *Geol. Mag.*, vol. **67**, pp. 218–240, 1930; The heavy mineral suites of the Uganda granites: *Uganda Geol. Survey, Ann. Rept.*, **1929**, pp. 40–41, 1930; The unroofing of the Dartmoor granite and the distribution of its detritus in the sediments of southern England: *Geol. Soc. London Quart. Jour.*, vol. **87**, pp. 62–96, 1931; The heavy mineral suites and correlation of the Uganda granites: *Uganda Geol. Survey, Ann. Rept.*, **1930**, pp. 38–39, 1931; Appendix I to the geology of southwest Ankole: *Geol. Survey Uganda, Memoir* **11**, pp. 196–213, 1932.

Wells[24] in 1931 severely criticized the methods and conclusions of Groves. He shows that over a period of three years Groves reversed himself on the age that he would assign to the Channel Island granites. Wells says: "Comparing rocks of the same petrographic type, of the same genetic history, and occurring in comparable situations in relation to the contemporaneous fold axes, we shall expect identity of mineral composition if, and only if, the rock bodies have had the same cooling history—in other words, if they are alike in size, manner of injection, thickness of roof, etc."

He states that the pneumatolytic accessories will be most abundant in the higher parts of an intrusion and that ultimately they will be completely removed by erosion. "Therefore, . . . , the minerals of this class are without value as indicators of age."

Contamination accessories, to Wells' mind, are completely lacking in time significance. The value of "secondary accessories," by which Wells means such paulopost or deuteric minerals (minerals produced during the later stages as a direct consequence of the consolidation of the magma of the rock) as members of the chlorite, serpentine, and epidote groups, for correlation is minimized.

Wells next takes up certain "normal accessories" (those developed independently of any special controlling factors such as high flux content) and one by one eliminates them from the group that he considers of possible value for the uses claimed for accessory-mineral studies. Finally he states that zircon and possibly some other minerals, at least in theory, might be unique in certain rocks and therefore of value.

In conclusion Wells says: "Only in so far as the cooling history of an intrusion has been unique can one reasonably expect the rocks to yield a distinctive heavy-mineral suite: only in as much as the cooling history of two or more intrusions has been alike can one expect similarity in heavy-mineral content. To use heavy minerals for correlation is to claim both the uniqueness of the first, and the similarity of the second supposition. It is asking much, and in the writer's opinion, is not proven."

Groves[25] answers Wells' contentions by pointing out that the reason he assigns different ages to some of the same granites in the Channel Islands in different papers is that certain stratigraphic links have changed at the hands of other workers, owing in part to his work with the heavy minerals.

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[24] Wells, A. K., The heavy-mineral correlation of intrusive igneous rocks: *Geol. Mag.*, vol. **68**, pp. 255–262, 1931.

[25] Groves, A. W., The heavy-mineral correlation of igneous rocks: *Geol. Mag.*, vol. **68**, pp. 526–527, 1931.

He says that it is to be expected that "normal accessories" would be less affected by the size of the intrusion, manner of injection, thickness of the roof, etc., than the major constituents, because these minerals normally crystallize before disturbing influences can act on them.

He points out that even the pneumatolytic minerals have some correlation value. In their almost complete lack of beryllium minerals, the Armorican granites of Devon and Cornwall, Channel Islands, Normandy and Brittany contrast strongly with the Tertiary granites of the Mourne Mountains.

In summation he says that several writers have amply proved that generic features distinguish Armorican granites from pre-Cambrian, Caledonian, and Tertiary masses, while at the same time more specialized characters permit distinction between the heavy mineral assemblages of single intrusions.

Other British contributors to the accessory mineral studies of igneous and metamorphic rocks during the period 1923 to 1932 include Chatterjee,[26] Ghosh,[27] Grantham,[28] Leech,[29] Mackie,[30] and Smithson.[31] All these writers place more or less confidence in the use of studies of accessory minerals in the correlation or differentiation of igneous and metamorphic masses and in problems of provenance.

[26] Chatterjee, M., The accessory mineral assemblage of the Bodmin Moor granite (Cornwall): *Geol. Assoc. London Proc.*, vol. **40**, pp. 147–152, 1929.

[27] Ghosh, P. K. Petrology of the Bodmin Moor granite (eastern part), Cornwall: *Mineralog, Mag.*, vol. **21**, pp. 285–309, 1927; The mineral assemblage of the Falmouth granite (Cornwall): *Geol. Assoc. London Proc.*, vol. **39**, pp. 332–338, 1928.

[28] Grantham, D. R., The petrology of the Shap granite: *Geol. Assoc. London Proc.*, vol. **39**, pp. 299–331, 1928.

[29] Leech, J. G. C., St. Austell detritals: *Geol. Assoc. London Proc.*, vol. **40**, pp. 139–146, 1929.

[30] Mackie, William, The principles that regulate the distribution of particles of heavy minerals in sedimentary rocks, as is illustrated by the sandstones of the northeast of Scotland: *Edinburgh Geol. Soc. Trans.*, vol. **11**, pp. 138–164, 1923; The source of the purple zircons in the sedimentary rocks of Scotland: *Idem*, pp. 200–213; Dumortierite in British rocks: *Idem*, p. 352, 1925; The heavier accessory minerals in the granites of Scotland: *Idem*, vol. **12**, pp. 22–40, 1928; The heavy minerals in the Torridon sandstone and metamorphic rocks of Scotland and their bearing on the relative ages of these rocks: *Idem*, pp. 181–182.

[31] Smithson, Frank, Geological studies in the Dublin district—I, The heavy minerals of the granite and the contiguous rocks in the Ballycorus district: *Geol. Mag.*, vol. **65**, pp. 12–25, 1928; The petrography of the northern portion of the Leinster granite: *Idem*, vol. **69**, pp. 465–474, 1932.

Each year since the formation of the National Research Council Committee on Accessory Minerals, in 1931, Winchell has summarized the work along this line done or in progress in North America. Much of it has been the work of graduate students at various universities under the direction of professors who were particularly interested in problems relating to accessory minerals. Several papers[32] have appeared, and more are to be expected in the near future.

Occasionally an investigator comes to a conclusion such as that reached by Jenks, who states that the heavy accessories are of little value to the petrographer. Marsden, however, shows that Jenks' data tend to support and not to disqualify the principles of work on heavy minerals.

Most of the recent workers with accessory minerals recognize that such studies are still in their infancy. Nearly all are willing to grant the soundness of some of the basic principles involved. Most recognize the value for correlation, differentiation, and other purposes of studies of accessory minerals under favorable conditions, even in the present rudimentary state of our knowledge. In general, the North American workers in this field show a tendency to advance cautiously, taking full cognizance of the difficulties and limitation of such studies. For example, Wright[33] says, "The accessories of igneous masses from many areas and of different ages, however, need to be studied in great detail before further broad and general conclusions can be presented regarding their usefulness in correlating and delimiting granite batholiths. The results of the investigations completed to date assuredly are encouraging enough to warrant a much more extended study of the accessories in granites than hitherto has been undertaken."

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[32] Reed, J. C., and Gilluly, James, Heavy-mineral assemblages of some of the plutonic rocks of eastern Oregon: *Am. Mineral.*, vol. **17**, no. 6, June 1932.

Wright, J. F., Accessory minerals in the study of granite batholiths: *Royal Soc. Canada Trans.*, 3d ser., vol. **26**, sec. 4, pp. 251–265, 1932.

Singewald, Q. D., Alteration as an end phase of igneous intrusion in sills on Loveland Mountain, Park County, Colo.: *Jour. Geology*, vol. **40**, pp. 16–20, 1932.

Boos, M. F., and Boos, C. M., Granites of the Front Range: The Longs Peak-St. Vrain batholith: *Geol. Soc. Am. Bull.*, vol. **44**, pp. 72–73, 1933.

Lamey, Carl A., The intrusive relations of the Republic granite: *Jour. Geology*, vol. **41**, pp. 487–500, 1933.

Boos, M. F., Granites of the Front Range—The heavy minerals (abstract): *Geol. Soc. Am. Proc.*, 1933, p. 67, **1934.**

Boos, M. F., and Boos, C. M., Granites of the Front Range: The Longs Peak-St. Vrain batholith: *Geol. Soc. Am. Bull.*, vol. **45**, pp. 303–322, 1934.

Jenks, W. F., Heavy minerals in the syenite of Pleasant Mountain, Maine: *Am. Mineral.*, vol. **19**, pp. 476–479, 1934.

Stark, J. T., Heavy minerals in the Tertiary intrusives of central Colorado: *Am. Mineral.*, vol. **19**, pp. 586–592, 1934.

Marsden, Ralph W., Discussion of the paper "Heavy minerals in the syenites of Pleasant Mountain, Maine": *Am. Mineral.*, vol. **20**, pp. 132–135, 1935.

Taylor, G. L., Pre-Cambrian granites of the Black Hills: *Am. Jour. Sci.*, 5th ser., vol. **29**, pp. 278–291, 1935.

Tolman, Carl, and Koch, H. L., Accessory mineral suites in the granites of Missouri (abstract): *Am. Mineral.*, vol. **20**, p. 208, 1935.

Stark, J. T., and Barnes, F. F., The correlation of pre-Cambrian granites by means of heavy mineral analyses: *Geol. Mag.*, vol. **72**, no. 854, pp. 341–350, August 1935.

Newhouse, W. H., Opaque oxides and sulphides in common igneous rocks: *Geol. Soc. Am. Bull.*, vol. **47**, pp. 1–52, 1936.

[33] Wright, J. F., *op. cit.*, p. 264.

FURTHER STUDIES OF THE ZEOLITES

A. N. Winchell, *University of Wisconsin, Madison, Wisconsin.*

Twelve years ago the writer proposed a new theory of the composition of the zeolites[1] according to which those zeolites which are not essentially fixed in composition show variations in their alkali or alkaline earth metal, not under the control of valence, but in the same way as in the feldspars. It was recognized at that time that variations in composition under valence control are found in nature, and can be produced artificially, but it was suggested that such variations are secondary in origin, even when found in nature. Although this theory was unlike any previous conception of the composition of the zeolites and even directly contrary to most of them, it has not been seriously challenged[2] since that time, and seems to be winning gradual acceptance by those who are making careful studies of the hydrous equivalents of the feldspars.

In the original study of the zeolites the relation between variations in the Na:Ca ratio and the Si:Al ratio was studied by means of square diagrams essentially based on these two ratios. At the same time the diagrams were intended to be devised in such a way that any single point on one of them would represent a complete analysis in terms of the four molecules at the corners of the square. In this respect the diagrams were not accurate, since the center point should represent equal parts[3] of the two molecules at the ends of each diagonal, but cannot do so since these sums are not equal to each other.

During the last decade many new analyses of zeolites have been published. Accordingly it is now possible, not only to correct the diagrams previously published, but also to prepare diagrams based on much new information, some of which is doubtless more accurate than previously available. This article describes an attempt to accomplish these ends.

Considering the square formerly used for the study of thomsonite, the molecules concerned were

$Ca_3Al_6Si_{10}O_{32}\cdot Aq$ $\qquad$ $Na_6Al_6Si_{10}O_{32}\cdot Aq$
$Ca_5Al_{10}Si_6O_{32}\cdot Aq$ $\qquad$ $Na_{10}Al_{10}Si_6O_{32}\cdot Aq.$

In order to change these so that they will satisfy the condition already explained those in the first line must be taken five times and those in the second line three times. Then the Ca molecules will have the same number of Ca atoms and of Al atoms; they will differ only in Si atoms and O atoms. The same is true of the Na molecules. This shows that the Al:Si ratio must be changed by increasing the Si atoms without changing the Al atoms. Accordingly, if we begin with $CaAl_2Si_2O_8$ and $Na_2Al_2Si_2O_8$ which are the molecules containing the minimum tenor of silica in zeolites, an increasing tenor of silica must be represented by $CaAl_2Si_3O_{10}$, $CaAl_2Si_4O_{12}$, etc. In order to show a considerable difference it may be desirable to use $CaAl_2Si_6O_{16}$ and $Na_2Al_2Si_6O_{16}$ as the other corner molecules of the square, as shown in Fig. 1. On this square the lines connecting points having equal numbers of (Ca+Na) atoms for a given number of oxygen atoms are straight. They are not parallel, but are diagonal in their general direction. The numbers on them in the figure express the number of (Ca+Na) atoms for 80 oxygen atoms. The composition of many zeolites

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[1] *Am. Mineral.*, vol. **10**, pp. 88, 112, 145 and 166, 1925.

[2] E. T. Wherry (*Am. Mineral.*, vol. **10**, p. 342, 1925) took exception to the theory as applied to thomsonite; he asked for optical evidence (of an isomorphous series), which the writer supplied. (*Am. Mineral.*, vol. **11**, p. 82, 1926.)

[3] Dr. N. L. Bowen kindly called the writer's attention to this method of testing a square diagram. See also *Am. Mineral.*, vol. **20**, p. 773, 1935.

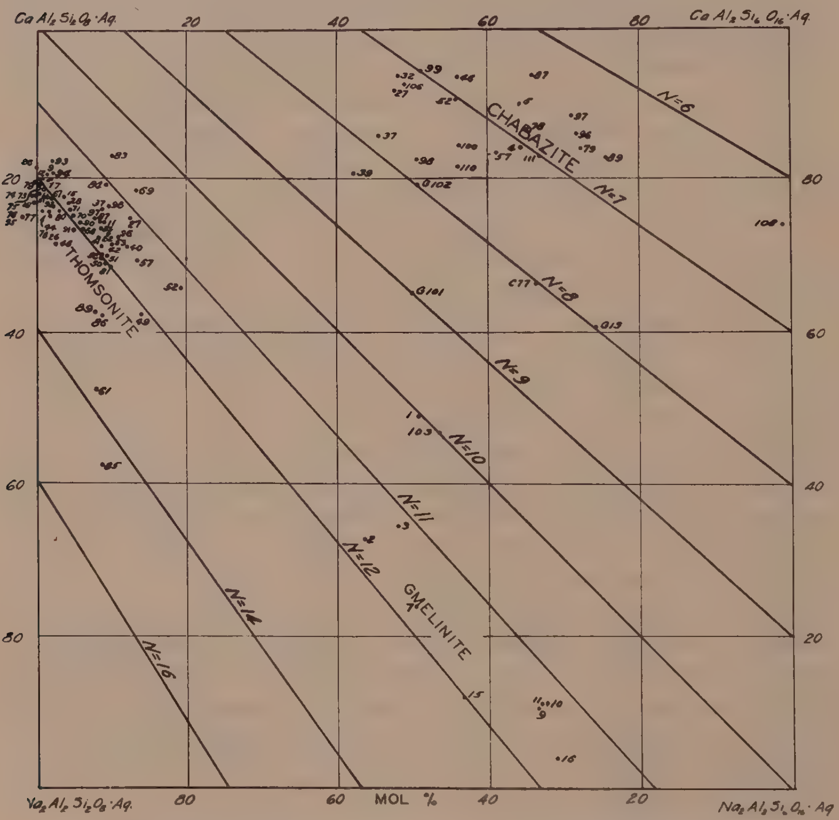

FIG. 1. Variations in composition in thomsonite, chabazite, and gmelinite.

can be shown on this square, but stilbite and heulandite may contain more SiO_2, and mordenite and ptilolite contain much more silica. To show these zeolites it is necessary to use a square which may be shown adjoining the first one; it has $CaAl_2Si_{10}O_{24} \cdot Aq$ and $Na_2Al_2Si_{10}O_{24} \cdot Aq$ as the silica-rich molecules. A few samples of ptilolite are even more siliceous than can be expressed inside this square.

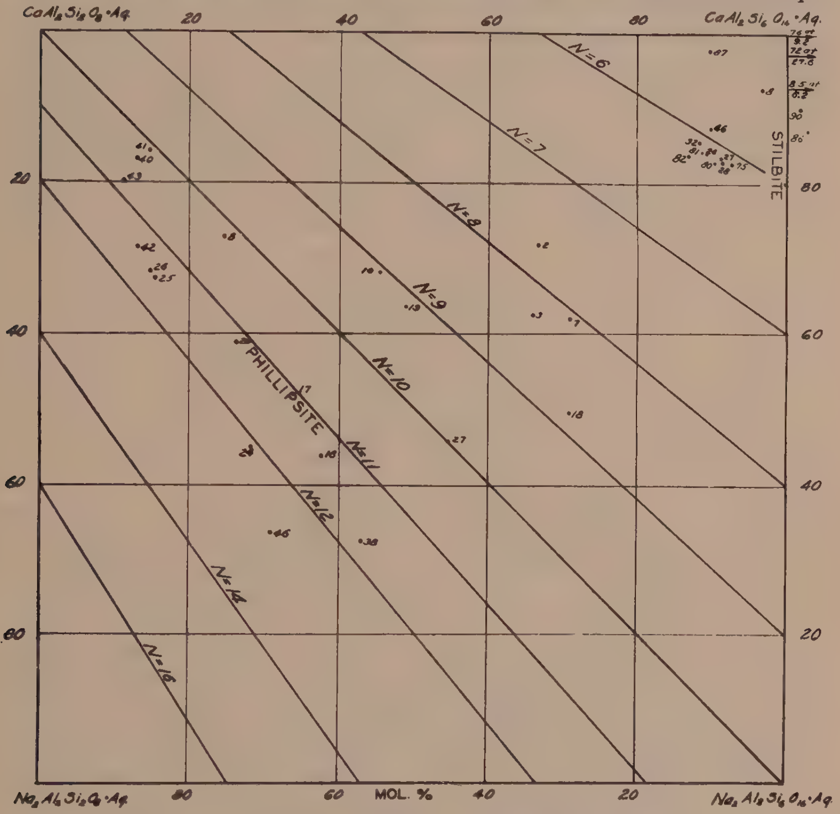

FIG. 2. Variations in composition in phillipsite and stilbite.

The distribution of points[4] expressing the best analyses of thomsonite

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[4] To find the position of the point representing any analysis it is only necessary to find: (a) the per cent. of Na_2O molecules in the total Na_2O+CaO molecules, and (b) the per cent. of silica-rich molecules in the total of silicate molecules; this may be accomplished from the silica and alumina molecules by means of the relation:

$$\% \text{ silica-rich molecules } (Si_6) = \frac{1/4(SiO_2-2Al_2O_3)100}{Al_2O_3} \text{ for Figs. 1 and 2.}$$

$$\% \; Si_{10} \text{ molecules} = \frac{1/4(SiO_2-6Al_2O_3)100}{Al_2O_3} \text{ in right hand square of Fig. 3.}$$

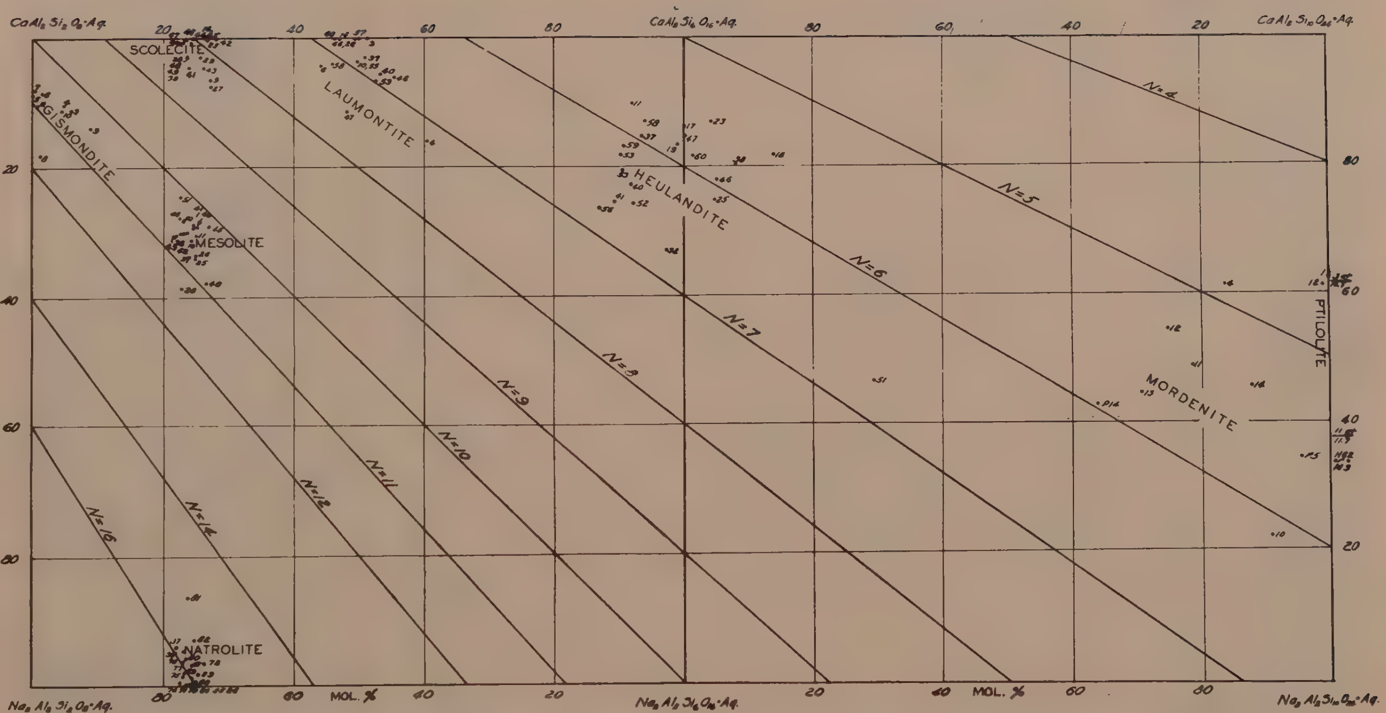

FIG. 3. The composition of gismondite, scolecite, mesolite, natrolite, laumontite, heulandite, mordenite, and ptilolite.

shown on Fig. 1 indicates some variation of composition under valence control (secondary?), as well as distinct and more common variation as in feldspars. On the same figure the composition of chabazite is seen to vary chiefly as in the feldspars, but that of gmelinite varies chiefly under valence control; the writer has suggested that this is due to secondary changes.

The remarkably random distribution of points expressing the best analyses of phillipsite is shown in Fig. 2, as well as the more compact grouping of good analyses of stilbite.

Two squares are shown side by side in Fig. 3 so as to give the complete picture of the distribution of points representing heulandite and their relation to mordenite and ptilolite. On the same diagram are shown the variations of composition of laumontite and of gismondite, as well as the approximately constant composition of scolecite, mesolite, and natrolite. It is possible to find variation of composition under the control of valence in nearly all zeolites, but in many cases this is subordinate to variation of the feldspar type, and it is perhaps always secondary.

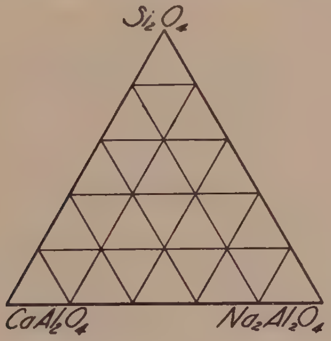

FIG. 4. Theoretical components (not end-members) of zeolites.

These squares express variations of composition in terms of addition of equal parts of silica to an original molecule and, therefore, equal distances on them do not express equal changes of composition. This may be more readily understood by noting the fact that it would be necessary to add an *infinite* amount of a molecule, B, to the original molecule, A, in order to complete the change from A to B, which is half accomplished when one molecule of B is added to one of A, and only changed from 90 per cent. to 90.9 per cent. when one molecule of B is added to a mixture of A+9B. Therefore it is highly desirable to devise a different diagram.

As already explained, one extreme of the change in composition of zeolites is pure silica; it follows that another extreme must be a molecule with no silica. Disregarding soda it is easy to see that this must contain

CaO and Al_2O_3 in equal parts. Therefore the molecule is $CaAl_2O_4$; and a silica molecule of equal oxygen content must be Si_2O_4. The soda molecule corresponding to $CaAl_2O_4$ is clearly $Na_2Al_2O_4$. These may be arranged on a triangle as shown in Fig. 4.

What part of this triangle represents the composition of zeolites? The minimum tenor of SiO_2 in zeolites is found in some samples of thomsonite, the composition of which (omitting Na_2O and H_2O) may be written: $CaAl_2Si_2O_8$. This is the composition expressed by a point midway between $CaAl_2O_4$ and Si_2O_4. The corresponding sodium molecule is $Na_2Al_2Si_2O_8$ and pure silica with the same oxygen content must be written Si_4O_8. Thus we obtain the molecules of Fig. 5, which corresponds with the upper half of Fig. 4. The same molecules are used in Figs. 6–8. In these triangular diagrams there is no distortion, and equal distances represent equal changes of composition. Horizontal lines express variation of composition under valence control (Ca for 2 Na), and diagonal lines express variations of composition of the feldspar type (CaAl for NaSi); the numbers on these diagonal lines give the number of (Ca+Na) atoms for 80 oxygen atoms. It is impracticable to number the points representing analyses since they are too close together.

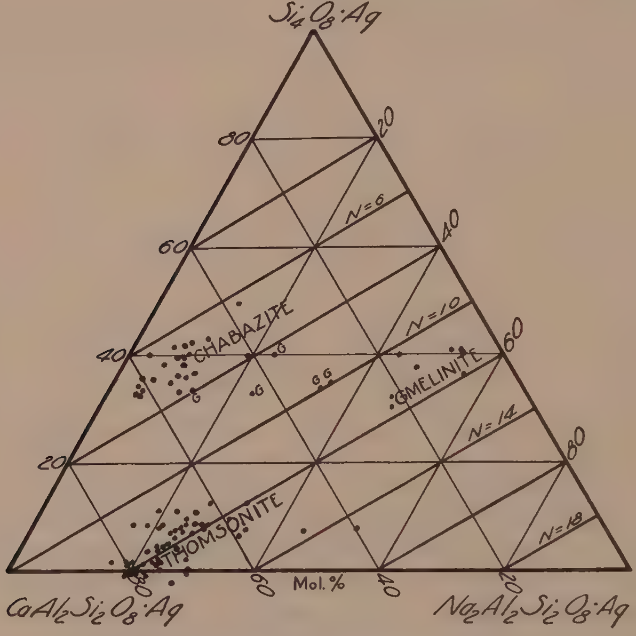

FIG. 5. Variations in composition of thomsonite, chabazite, and gmelinite.

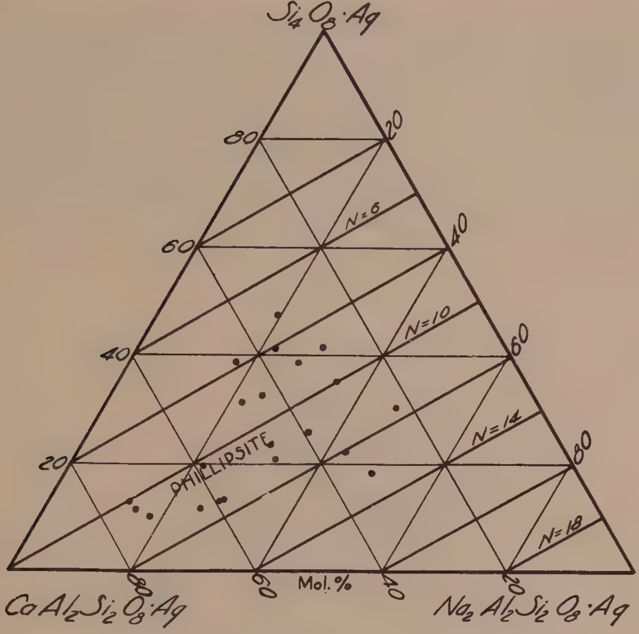

FIG. 6. Variations of composition in phillipsite.

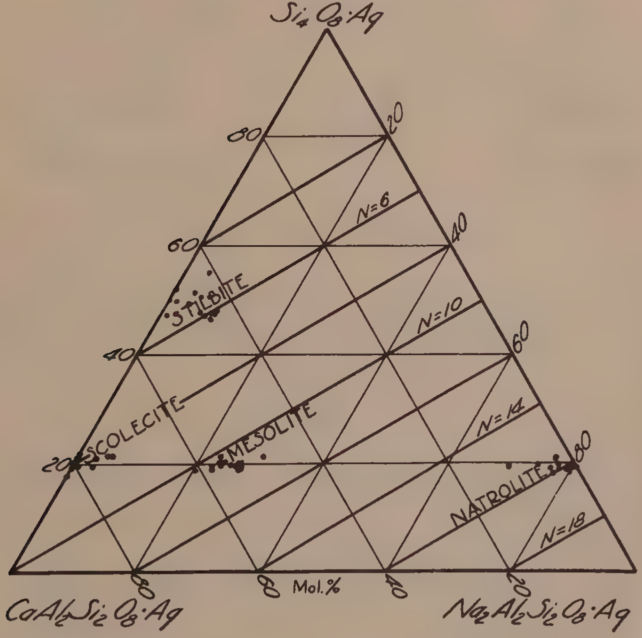

FIG. 7. Composition of scolecite, mesolite, natrolite, and stilbite.

The variations in composition of thomsonite are shown in Fig. 5, as well as those of chabazite and gmelinite. The wide scattering of points in Fig. 6 expresses the apparently lawless way phillipsite varies in composition, but all the points may be explained as due to the feldspar type of variation (with $N=10$), plus (secondary?) variation under valence control. Scolecite, mesolite, and natrolite are nearly fixed in composition, as shown in Fig. 7; stilbite varies only a little more than the others.

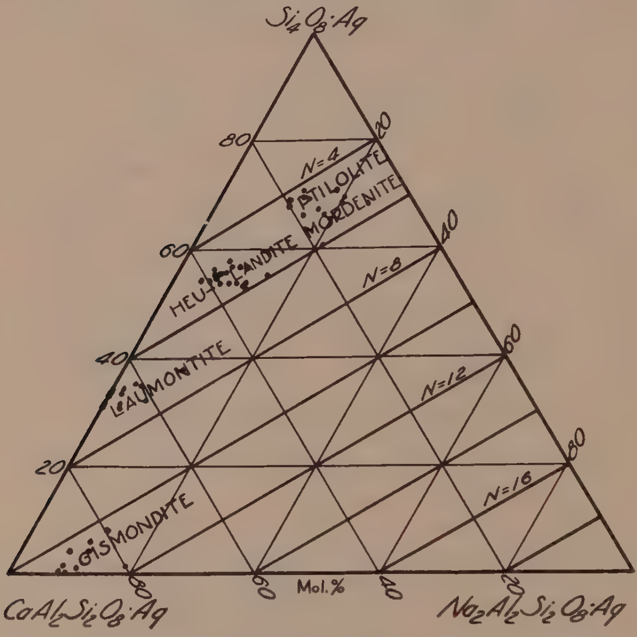

FIG. 8. Variations of composition in gismondite, laumontite, heulandite, mordenite, and ptilolite.

Laumontite and gismondite vary a little more, as shown in Fig. 8, which also shows the relation between heulandite, mordenite and ptilolite; heulandite and mordenite seem to form a (discontinuous?) series.

It is a surprise to the writer to discover in this way that some zeolites are seventy per cent. silica[5] (Si_4O_8) with only thirty per cent. of molecules

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[5] To find the point representing any analysis of a zeolite on any one of these triangular diagrams it is only necessary to use: (a) the per cent. of Na_2O molecules in the total Na_2O+CaO molecules, and (b) the per cent. of Si_4O_8 which may be obtained from:

$$\%\ Si_4O_8=\frac{1/4(SiO_2-2Al_2O_3)100}{1/4(SiO_2-2Al_2O_3)+Al_2O_3}.$$

Analyses in which Al_2O_3 molecules differ materially from Na_2O+CaO molecules are probably incorrect and should not be used.

which have the minimum tenor of silica in zeolites. In this connection it may be worth while to state that the writer does not consider any of the molecules used on these triangular diagrams to be end-members of any zeolite, though gismondite has an end-member molecule which is not very different from $CaAl_2Si_2O_8 \cdot Aq$.

Variations of optical properties corresponding with these variations in composition in zeolites are not easily defined, partly because the optical properties depend upon both types of variation in composition, and also upon the state of hydration, which is not always complete. Nevertheless, the relations between variations in optic properties and variations in composition (of the feldspar type) in thomsonite are illustrated in Fig. 9.

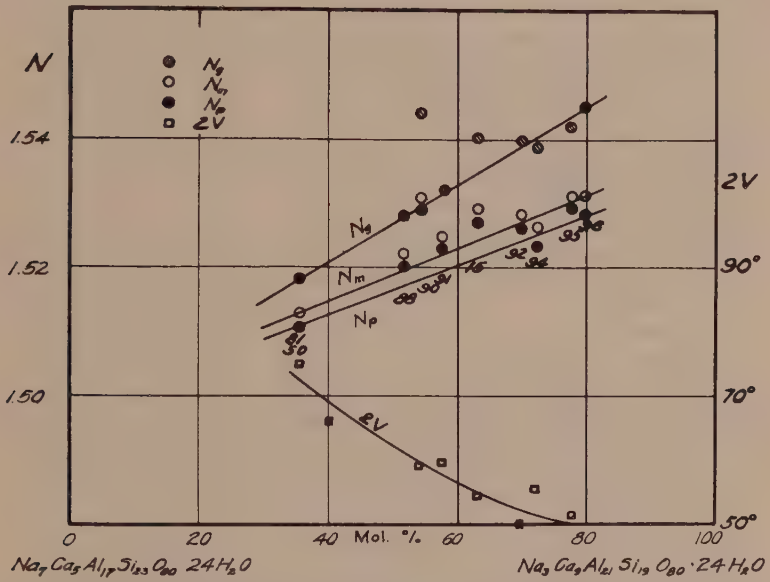

FIG. 9. Variations in composition and optic properties in thomsonite. Based on data of M. H. Hey: *Mineral. Mag.*, vol. **23**, p. 51, 1932, and others.

REFERENCES FOR ANALYSES

FIG. 1. Thomsonite numbers 9, 12, 15, 18, 26–28, 31, 36–42, 44, 46, 49–53, 56, 57, 61, 66 and 67 are Doelter's[1] numbers and 69 to 74 are listed on p. 93, *Am. Mineral.*, vol. **10**, 1925.

75. Peekskill, N. Y. Phillips, A. H.: *Am. Mineral.*, vol. **9**, p. 240, 1924.
76. Cyclopean Isles, Sicily. Di Franco, S.: *Per. Mineral.*, vol. **3**, p. 197, 1932.
77. Sextant Rapids, Ont. Walker, T. L.: *Univ. Toronto Geol. Ser.*, vol. **32**, p. 5, 1932.

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[1] *Hdb. Mineralch.*, **II**, 3, p. 16, 1921.

78. Grant Co., Ore. Hewett, D. F., *et. al.: Proc. U. S. Nat. Mus.*, vol. **73,** 1928, Art. 16.
79. Valle di Vin. Gennaro, Va.: *Atti Accad. Sci. Torino*, vol. **64,** p. 133, 1929.
80. Monte Rosa. Gennaro, Va.: *loc. cit.* Also *Min. Abst.*, vol. **4,** p. 376, 1930.
81. Table Mt., Colo. Hey, M. H.: *Mineral. Mag.*, vol. **23,** p. 51, 1932.
82. Nolsö, Faroe Isl. Hey, M. H.: *loc. cit.*
83. Goble, Ore. Hey, M. H.: *loc. cit.*
84. Nolsö, Faroe Isl. Hey, M. H.: *loc. cit.*
85. Schieferberg, Bohemia. Hey, M. H.: *loc. cit.*
86. Hauenstein, Bohemia. Hey, M. H.: *loc. cit.*
87. Table Mt., Colo. Hey, M. H.: *loc. cit.*
88. Carmoney Hill, Co. Antrim. Hey, M. H.: *loc. cit.*
89. Leitmeritz, Bohemia. Hey, M. H.: *loc. cit.*
90. West Paterson, N. J. Hey, M. H.: *loc. cit.*
91. Bozen, Tyrol. Hey, M. H.: *loc. cit.*
92. Kaaden, Bohemia. Hey, M. H.: *loc. cit.*
93. Tuscany. Hey, M. H.: *loc. cit.*
94. Monte Somma. Hey, M. H.: *loc. cit.*
95. Old Kilpatrick. Hey, M. H.: *loc. cit.*
96. Aussig, Bohemia. Hey, M. H.: *loc. cit.*
97, 98. Disco Isl., Greenland. Gaertner, H. R., and Machatschki, F.: *Cent. Min.*, A, p. 365, **1927**.

Chabazite numbers 4, 5, 27, 32, 37, 39, 46, 52, 57, 77–79, 87, 89 and 96–99 are Doelter's numbers.

100. Boise Co., Idaho. Shannon, E. V.: *U. S. Nat. Mus., Bull.*, **131,** p. 357, 1926.
106. Grant Co., Ore. Hewett, D. F., Shannon, E. V., and Gonyer, F. A.: *Proc. U. S. Nat. Mus.*, vol. **73,** Art. 6, 1928.
108. Nova Scotia. Kappen, H. and Fischer, B.: *Min. Abst.*, vol. **4,** p. 317, 1930.
110, 111. Csódi-Berg, Hungary. Reichert, R. and Erdelyi, J.: *Tsch. Min. Pet. Mit.*, vol. **46,** p. 237, 1935.

Gmelinite numbers 1, 2, 3, 7, 9–11, 13 and 15 are Doelter's numbers:

16. Pinnacle Isl., N. S. Walker, T. L.: *Am. Mineral.*, vol. **7,** p. 100, 1922.
101–103. White Head, Ireland. Smith, G. F. H., Ashcroft, F. N. and Prior, G. T.: *Mineral. Mag.*, vol. **17,** p. 274, 1916.

Fig. 2. Phillipsite numbers 2, 3, 7, 8, 10, 16–19, 23–27, 38 and 40–43 are Doelter's numbers.

46. Honolulu. Dunham, K. C.: *Am. Mineral.*, vol. **18,** p. 369, 1933.
47. Leipa, Bohemia. Koenigsberger, J. and Müller, W. J.: *N. Jahrb. Bl. Bd.*, **44,** p. 402, 1921.

Stilbite numbers 12, 26–28, 32, 46, 72 and 76 are Doelter's numbers.

80. Partridge Isl., N. S. Parsons, A. L.: *Univ. Toronto Stud., Geol. Ser.*, **14,** p. 68, 1922.
81. Long Point, N. S. Parsons, A. L.: *loc. cit.*
82. Morden, N. S. Parsons, A. L.: *loc. cit.*
85. Gooseberry, W. Austral. Simpson, E. S.: *Min. Abst.*, vol. **5,** p. 94, 1932.
86. Piedmont. Resegotti, G.: *Min. Abst.*, vol. **5,** p. 83, 1932.
87. Grant Co., Ore. Hewett, D. F., Shannon, E. V. and Gonyer, F. A.: *Proc. U. S. Nat. Mus.*, vol. **73,** Art. 16, 1928.
88. Mt. Blanc. Bianchi, A. and Cavinato, A.: *Min. Abst.*, vol. **4,** p. 469, 1931.
89. Iceland. Kappen, H. and Fischer, B.: *Min. Abst.*, vol. **4,** p. 317, 1930.
90. Rove, Norway. Carstens, C. W.: *Min. Abst.*, vol. **3,** p. 25, 1926.

FIG. 3. Gismondite numbers 3 to 10 are Doelter's numbers.

11. Capo di Bove, Italy. Caglioti, V.: *Min. Abst.*, vol. **4**, p. 375, 1930.

Scolecite numbers 9, 16, 24, 25, 27–29, 39 and 40 are Doelter's numbers.

41. Digby Gut, N. S. Walker, T. L.: *Univ. Toronto Geol. Ser.*, **14**, p. 67, 1922.
42. Mull, Scotland. Radley, E. G.: *Trans. Roy. Soc. Edinb.*, vol. **51**, p. 1, 1915.
43. Bettolina, Italy. Gennaro, Va.: *Min. Abst.*, vol. **4**, p. 376, 1930.
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48. Syhadree Mts., India. Hey, M. H.: *Mineral. Mag.*, vol. **24**, p. 227, 1936.
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Mesolite numbers 10, 11, 25, 26 and 28 are Doelter's numbers.

38. Cape d'Or, N. S. Walker, T. L.: *Univ. Toronto Geol. Ser.*, **14**, p. 57, 1922.
39. Nova Scotia. Walker, T. L.: *loc. cit.*
40. Tiriolo, Italy. Panichi, V.: *Rend. Accad. Linc. Rom.*, vol. **20**, pp. 421, 518, 1911.
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45. Iceland, Hey, M. H.: *loc. cit.*
46. Bombay, India. Hey, M. H.: *loc. cit.*

50, 51. Berufjord, Iceland. Cavinato, A.: *Min. Abst.*, vol. **4**, p. 320, 1930.

Natrolite numbers 24, 25, 26, 29, 35, 37, are Doelter's numbers.

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68. Ice Valley, B. C. Phillips, A. H.: *Am. Jour. Sci.*, vol. **42**, p. 472, 1916.
69. Bohemia. Tschermak, G.: *Sitzb. Akad. Wiss. Wien*, vol. **126**, p. 544, 1917.
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77. Cape Blomidon, N. S. Hey, M. H.: *loc. cit.*
78. Salesl. Hey, M. H.: *loc. cit.*
80. De Beers Mine. Hey, M. H.: *loc. cit.*
81. Seiser Alp. Hey, M. H.: *loc. cit.*
82. Snake Hill, N. J. Hey, M. H.: *loc. cit.*

Laumontite numbers 3, 4, 6, 10, 14, 26, 39, 40, 46, 47 and 53 are Doelter's numbers.

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Heulandite numbers 11, 17–19, 23, 25, 32, 37, 38, 40, 41, 46 and 47 are Doelter's numbers.

51. Challis, Idaho. Shannon, E. V.: *U. S. Nat. Mus., Bull.* **131**, p. 346, 1926.
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53. Berufjord, Iceland. Slawson, C. B.: *Am. Mineral.*, vol. **10**, p. 305, 1925.
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58. Petite Passage, N. S. Parsons, A. L.: *Univ. Toronto Geol. Ser.*, **14,** p. 52, 1922.
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60. Berufjord, Iceland. Scheumann, K. H.: *Zeit. Krist.*, vol. **62,** p. 657, 1923.
62. Hoodoo Mts., Wyo. Pirsson, L. V.: *Am. Jour. Sci.*, vol. **40,** p. 232, 1890.
    This is the same as mordenite No. 3.

Mordenite numbers 3 and 4 are Doelter's numbers.

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11 to 14. Custer Co., Idaho. Shannon, E. V.: *U. S. Nat. Mus., Bull.* **131,** p. 346, 1926.

Ptilolite numbers 1, 2, 3 and 5 are Doelter's numbers.

11. Guadalcanar Isl. Tschermak, G.: *Sitz. Akad. Wiss. Wien*, vol. **126,** p. 59, 1917.
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14. Dome, Ariz. Bramlette, M. N. and Posnjak, E.: *Am. Mineral.*, vol. **18,** p. 167, 1933.

NOTES ON THE STRUCTURE OF SERPENTINES

J. W. GRUNER, *University of Minnesota, Minneapolis, Minn.*[1]

INTRODUCTION

Warren and Bragg published notes on the structure of chrysotile, $H_4Mg_3Si_2O_9$, in 1930.[2] They were able to show that the fibres possess a double chain structure resembling closely that of the amphiboles. The chains are only loosely joined at right angles to their elongation, probably by residual valencies. Tentative figures for the atomic coordinates along the *a* and *b* axes of the structure were given. No attempt was made by Warren and Bragg to establish the coordinates along the fibre axis (*c* axis), but they concluded from the sharpness of certain reflections that the structure shows little if any variability along the *c* axis. On the other hand variability along the *b* axis is not only conceded but thought likely. The present writer was engaged in the preparation of a manuscript when a paper by Selfridge appeared.[3] He showed that the serpentines may be classified into two main divisions, those which possess a structure like chrysotile, and others which are like antigorite. These findings are in perfect agreement with the present investigation. Therefore, it is unnecessary to repeat Selfridge's conclusions. The present writer went further in the *x*-ray investigation, however, as will be shown.

X-RAY DATA

Iron and copper radiations were used for the powder photographs with the result that the number of lines obtained for the same range of interplanar distances is two to three times as great as those Selfridge recorded with molybdenum radiation. The mineral powders were mounted with collodion on silk thread. The powder rods obtained were 0.8 mm. in diameter. No corrections were applied to the interplanar spacings which are slightly too low for $d > 2.00$ Å. Experience has shown that with minerals like the serpentines, which give many diffuse lines, the probable error in measuring is in the neighborhood of $\frac{3}{4}$ per cent. The antigorite structures give better diffraction patterns than the chrysotiles, in which most lines are very broad and diffuse. But even in antigorite the lines with *h*0*l* indices are unusually wide, indicating some distortion or irregularity parallel to the *c* axis, since the *h*00 reflections are sharp and well defined in both structures.

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[1] This study was aided by liberal grants from the Graduate School of the University of Minnesota.

[2] Warren, B. E., and Bragg, W. L.: *Zeit. Krist.*, vol. **76**, pp. 201–210, 1930.

[3] Selfridge, G. C. Jr.: *Am. Mineral.*, vol. **21**, pp. 463–503, 1936.

Tables 1 and 2 record the diffraction lines for chrysotile and antigorite structures. These tables were abridged after the appearance of Selfridge's paper.

Table 1. Comparison of Powder Photographs of Chrysotiles
Fe Radiation. Radius 57.3 mm.

		Thetford		Saganaga[1]		Chelmsford, Mass.	
No.	*Indices*	*d*	*I*	*d*	*I*	*d*	*I*
1				7.908	2	7.983	2
2	200	7.073	2	7.118	5	7.209	4
3				4.952	0.5	4.930	0.5
4		4.565	2				
5				4.457	2	4.457	3
6		4.380	1 ind.				
7		3.974	2	3.974	1	4.002	2
8	400	3.588	6	3.588	6	3.603	6
9				3.358	0.5		
10						3.013	1
11				2.856	0.5	2.849	1
12		2.706	0.5	2.727	0.5	2.712	0.5
13		2.588	1	2.573	2	2.577	3
14	$20\bar{2}$	2.549	1				
15	202	2.446	3	2.421	3	2.437	3b
16		2.299	0.5				
17	$40\bar{2}$	2.176	ind.				
18	402	2.085	1	2.078	1	2.080	0.5
19				1.903	0.5		
20	800	1.807	1	1.808	1	1.810	1
21		1.736	1	1.732	0.5	1.729	0.5
22		1.680	1	1.672	1	1.679	1
23				1.613	0.5		
24	$80\bar{2}$ 0120	1.519	3	1.519	4	1.520	4
25	802 1000	1.450	1	1.449	1	1.452	1
26				1.401	0.5		
27	204	1.300	1	1.297	2b	1.299	2b
28	1200	1.209	0.5	1.210	1	1.212	1
29		1.187	ind.	1.189	0.5	1.190	0.5

b = broad.
ind. = indistinct.
[1] Lake Saganaga, Ontario-Minnesota boundary.

TABLE 2. POWDER PHOTOGRAPHS OF ANTIGORITES
Unfiltered Fe Radiation. Radius 57.3 mm.

		Antigorite		"Precious Serpentine"		"Picrolite"	
		Antigorio Valley, Italy		Montville, N. J.		Bohemia	
No.	*Indices*	*d*	*I*	*d*	*I*	*d*	*I*
1	200	7.16	6	7.12	6	7.21	6
2						5.13	0.5
3	040	4.66	0.5	4.61	1	4.68	1
4						4.23	0.5
5	400β	3.96	2	3.95	2	3.99	1
6				3.81	0.5		
7	400	3.588	7	3.592	7	3.603	5
8		3.480	0.5	3.490	0.5	3.483	0.5
9		2.798	1	2.784	1	2.802	1
10	061			2.677	0.5	2.663	0.5 ind.
11	$20\bar{2}$	2.521	4	2.514	4	2.524	4
12	202?			2.450	0.5		
13	600	2.402	1	2.411	2	2.397	1b
14				2.370	0.5		
15				2.210	0.5	2.228	ind.
16	$40\bar{2}$	2.152	1b	2.150	2b	2.152	1b
17				2.012	0.5		
18		1.986	0.5	1.962	0.5		
19				1.880	0.5		
20	$60\bar{2}$	1.848	0.5	1.831	1	1.843	0.5b
21	800	1.808	1	1.808	1	1.810	1
22				1.778	1	1.781	0.5
23	0120β	1.723	0.5	1.722	1	1.727	1
24		1.695	0.5	1.693	0.5	1.697	0.5
25						1.661	0.5
26				1.584	0.5	1.590	0.5
27	0120	1.562	3	1.560	3	1.563	3
28	063	1.538	2	1.536	2	1.538	2
29	$80\bar{2}$	1.529	1	1.522	1	1.508	1b
30		1.509	1	1.503	1		
31				1.494	1		
32		1.478	0.5	1.472	0.5		
33		1.454	0.5	1.459	0.5		
34	1000	1.442	1	1.446	1	1.446	1
35		1.417	0.5	1.410	0.5	1.415	0.5
36				1.381	0.5	1.383	0.5
37				1.358	0.5		
38		1.342	0.5	1.341	0.5	1.341	0.5
39				1.328	0.5		

TABLE 2 (*Continued*)

		Antigorite		"Precious Serpentine"		"Picrolite"	
		Antigorio Valley, Italy		Montville, N. J.		Bohemia	
No.	*Indices*	*d*	*I*	*d*	*I*	*d*	*I*
40	004?	1.315	1	1.312	2	1.314	1
41		1.298	0.5	1.295	0.5	1.297	0.5
42	204?			1.284	0.5	1.284	0.5
43				1.273	0.5	1.266	0.5
44		1.259	0.5	1.258	0.5		
45				1.244	0.5		
46	1200	1.201	1	1.206	1	1.205	1

b = broad.
ind. = indistinct.

It will be noticed that the values for *d* for planes with *h*00 indices are very similar in the two structures. Any other apparent similarity may be accidental, however. The indices which have been assigned to certain planes in Tables 1 and 2 are based on the assumption that the dimensions of the unit cell, as given by Warren and Bragg for chrysotile, are essentially correct and apply also to antigorite structures. The most accurate measurement is that of a_0 which varies between 14.40 Å and 14.52 Å for different varieties, b_0 varies between 18.50 Å and 18.74 Å, and c_0 between 5.28 Å and 5.36 Å. β is close to 93°. Making use of the atomic coordinates given by Warren and Bragg for the *a* and *b* directions, and of the intensities in the powder photographs, a great deal of time was spent in trying to find the *c* (or *Z*) coordinates. By shifting the double chains parallel to the *c* axis, but preserving the symmetry of space group C_{2h}^3, no very convincing agreement could be found between theoretical and observed intensities. The actual structure of chrysotile must vary therefore to some extent from the ideal one given by Warren and Bragg.

The minerals with antigorite structure give a greater number and better lines than chrysotile. On the assumption that this structure differs from chrysotile only in a shift of the chains parallel to *c*, no agreement could be found with observed intensities. It appears, therefore, that the structures are only closely similar to each other with respect to the *h*00 planes.

Very interesting observations were made on platy antigorite from the type locality, the Antigorio Valley. This material evidently possesses a sort of cleavage due to an orientation of submicroscopic fibres or plates. This has been proved by taking x-ray photographs of small plates of the material inclined at different angles to the zero beam. Certain indices were assumed for lines in the powder photographs (Table 2). It was also suspected that the megascopic platy structure of antigorite was parallel to 100. When a plate was inclined to the zero beam in such a way that theoretically a certain plane should have reflected with unusual intensity,

TABLE 3. THEORETICAL AND OBSERVED REFLECTIONS FROM ORIENTED PLATES OF ANTIGORITE

Zero beam at indicated angles to plane of plate

Indices	Θ°	0°		22½°		45°		67½°		90°	
		right	left	right	left	right	left	right	left	right	left
		+	−	−	−	−	−	−	−	−	−
200	7°45′	++	+	−	+	+	+	−	−	−	−
		−	−	−	−	−	−	+	−	−	−
040	11 58	−	−	−	−	−	−	+	−	+	+
		+	−	−	++	−	−	−	−	−	−
400	15 37	++	+	−	+++	+	+	−	−	−	−
		−	−	+	−	+	−	+	−	+++	+++
$20\bar{2}$	22 31	−	+	+	+	++	−	+	+	+++	+++
		−	−	−	+++	−	−	−	−	−	−
600	23 43	−	−	−	+++	−	−	−	−	−	−
		−	+	+	−	+	−	+	+	+	+
$40\bar{2}$	26 40	−	+	+	−	+	−	+	+	+	+
		+	+	−	−	−	−	−	+	−	−
$60\bar{2}$	31 31	−	−	−	−	−	+	−	+	−	−
		−	−	−	++	−	+	−	−	−	−
800	32 18	−	−	−	++	−	++	−	−	−	−
		−	−	+	−	++	−	−	−	−	−
0120	38 12	−	+	+	−	++	−	−	−	+	+
		−	−	−	−	++	−	−	−	−	−
063	38 54	−	−	+?	−	+++	−	−	−	−	−
		+	+	−	−	−	−	+	+	+	+
$80\bar{2}$	39 10	+	+	−	−	−	−	+	+	+	+
		−	−	−	−	−	++	−	−	−	−
1000	42 04	−	−	−	+	−	+++	−	−	−	−
		−	−	+	−	++	−	+	−	−	−
004	47 16	−	+	+	−	++	−	+	−	+?	+?
		+	+	+	−	+	−	−	+	+	+
6120	47 16	−	+	+	−	+	−	−	−	+?	+?
		+	+	+	−	+	−	+	+	−	−
204	48 06	−	+	+	−	+	−	+	+	−	−

the observed reflection agreed as well as could be expected. These observations are tabulated in Table 3. The inclinations of the plates are given at the top of the table. "Right" and "left" refer to the position of the reflection on the film to the right or left of the zero beam, respectively. The sign + means a certain reflection is present, − indicates its absence. The number of + symbols indicate intensity. The upper rows are the theoretical expectations, the lower, the observed reflections.

The data indicate that the indices chosen for the reflections are most probably correct, although there is no way of distinguishing between $20\bar{2}$ and 202, $40\bar{2}$ and 402, $80\bar{2}$ and 802, respectively, as long as the β angle is unknown.

It is certain, however, that in platy antigorite the larger structural units have a parallel or subparallel arrangement with respect to the plane (100), and not with regard to any fibre axis. Whether that means that the antigorite structure is more sheet-like than chain-like is still unknown. This holds true in spite of the fact that some "picrolites" and "baltimorites," which unquestionably appear fibrous in the hand specimen, are identical in structure to antigorite. Massive serpentines like the precious variety from Montville, N. J. also have this structure. On the other hand, massive serpentine from the wall rock of a cross fibre vein of chrysotile shows the chrysotile structure.

CONCLUSIONS

The serpentines[4] are divided into two groups, the chrysotiles and antigorites. All other variety names, as already advocated by Selfridge, should be discontinued. The name serpentine should be used where it is impossible to distinguish between the two.

It is believed that dimorphism exists, as chemical analyses show no appreciable differences in the composition of the two structures. Often x-rays will be the only means for identification, since optical properties are very similar in chrysotiles and antigorites. Chrysotile possesses a chain structure as shown by Warren and Bragg. They assigned coordinates to the atoms in these chains for the a and b axes, and computed intensities of reflections for some of the prism and pinacoid planes (exclusive of the basal pinacoid). It is easy to assign atomic coordinates for the c direction on the assumption that the chains are undistorted in this direction. This was done and theoretical intensities for $h0l$ and other planes were calculated. These were in poor agreement with the observed intensities. Therefore, some adjustments in the coordinates of chrysotile, especially in the *a* direction, seem necessary.

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[4] Ishkyldite described by Syromyatnikov, *Am. Mineral.*, vol. **21**, p. 48, 1936, is excluded from this discussion.

The antigorite structure may be chain-or sheet-like. The platy mineral from the type locality shows a definite subparallel to parallel arrangement with respect to (100), and not with regard to any fibre axis.

ORIENTED INCLUSIONS OF MAGNETITE AND HEMATITE IN MUSCOVITE

CLIFFORD FRONDEL AND GEORGE E. ASHBY

Mass. Institute of Technology, Cambridge, Mass., and Brooklyn, New York.

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INTRODUCTION

Extremely thin, oriented, black or smoky brown inclusions of iron oxide frequently occur between the basal cleavages of muscovite, and have been briefly described by a number of writers (1–16). The presence of such inclusions in mica may affect the value for commercial purposes by impairing the splitting qualities and transparency, and by decreasing the dielectric strength.

The included mineral has generally been called magnetite. However, it is found that two contrasting types of inclusions can be distinguished. One type, of relatively rare occurrence and hitherto little known, is definitely magnetite. The second type of inclusion, of which the lattice- and dendrite-like growths in the Pennsbury, Pennsylvania, muscovite are typical, and comprising most of the so-called magnetite inclusions mentioned in the literature, probably consists of hematite.

The material investigated in the present study included a collection of approximately 500 specimens of muscovite containing inclusions collected by one of the authors (G. E. A.) from 26 localities on Manhattan Island, New York City; similar specimens from the collection of the New York Mineralogical Club; and a suite of mica sheets and other specimens from the collection of the American Museum of Natural History.

The writers are indebted to Mr. Herbert P. Whitlock for opportunity to examine the material from the Museum, and to Dr. Frederick H. Pough for a critical reading of the manuscript.

DESCRIPTION OF SPECIMENS*

MAGNETITE INCLUSIONS

Magnetite inclusions are readily distinguished by their color, habit, and the presence of parting cracks. The inclusions are frequently so thin as to be translucent, and are then pure gray, iron-gray or lavender gray in color. Smoke-gray and light drab tints of color are frequently seen in the thinnest crystals. Opaque crystals are iron-black in color and fairly lustrous.

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* The following description of the inclusions refers generally to specimens from all of the observed localities.

Parting Cracks. Octahedral parting cracks, arranged in three sets intersecting at 60°, are almost invariably present in the crystals (Figs. 1, 2, 6, 7). The arrangement of the cracks in a 60° pattern identifies the inclusions as plates flattened on (111).

The cracks are open, but as a rule draw together at the margin of the crystal. The development is not always uniform. In some instances, a crystal may be blocked out into relatively large hexagonal segments by a strongly developed series of wide cracks, with the interior of each segment fissured on a smaller scale. The interior cracks are then relatively narrow and fade out at the margins of the larger segments. Sometimes the crystal is blocked out into a net-like pattern of small rhombic segments by the development of but two of the sets of cracks. Several instances were noted in which the cracks outlined a single hexagon inscribed in the hexagonal outline of the crystal. Again, three small cracks only may radiate from the center of the crystal. Fishbone patterns were also seen. The cracks can be discerned in all but the thinnest, pure gray or smoke-gray and nearly transparent, inclusions.

A few crystals, in muscovite from 176th Street, between Audubon and St. Nicholas' Avenues, New York City, were found to be peculiar in that they showed a second series of cracks at right angles to the ordinary series (Fig. 6). Cracks in this orientation could be caused only by a parting parallel to the dodecahedron or to a trapezohedron. It was not possible, however, to determine to which of these forms the parting cracks belonged. A minor dodecahedral parting in magnetite has been observed by Kemp (17).

The characteristics of the cracks suggest that they have been formed by the contraction of the crystals. Twinning has obviously played no part in their formation. Although evidence of secondary mechanical working is usually visible in the muscovite crystals, the cracks appear to bear no relation to such disturbances. Efforts to obtain parting cracks experimentally by flexing or shearing foils of mica containing inclusions were unsuccessful.

Habit; Size. The magnetite inclusions generally have a hexagonal outline, with the parting cracks perpendicular to the sides (Figs. 1, 5, 7). This position of the cracks identifies the laterally bounding faces as those of the dodecahedron. Although several thousand crystals were noted, from twenty-two localities, all were bounded laterally by dodecahedral faces, at least in part. This fact is remarkable, since the form of most

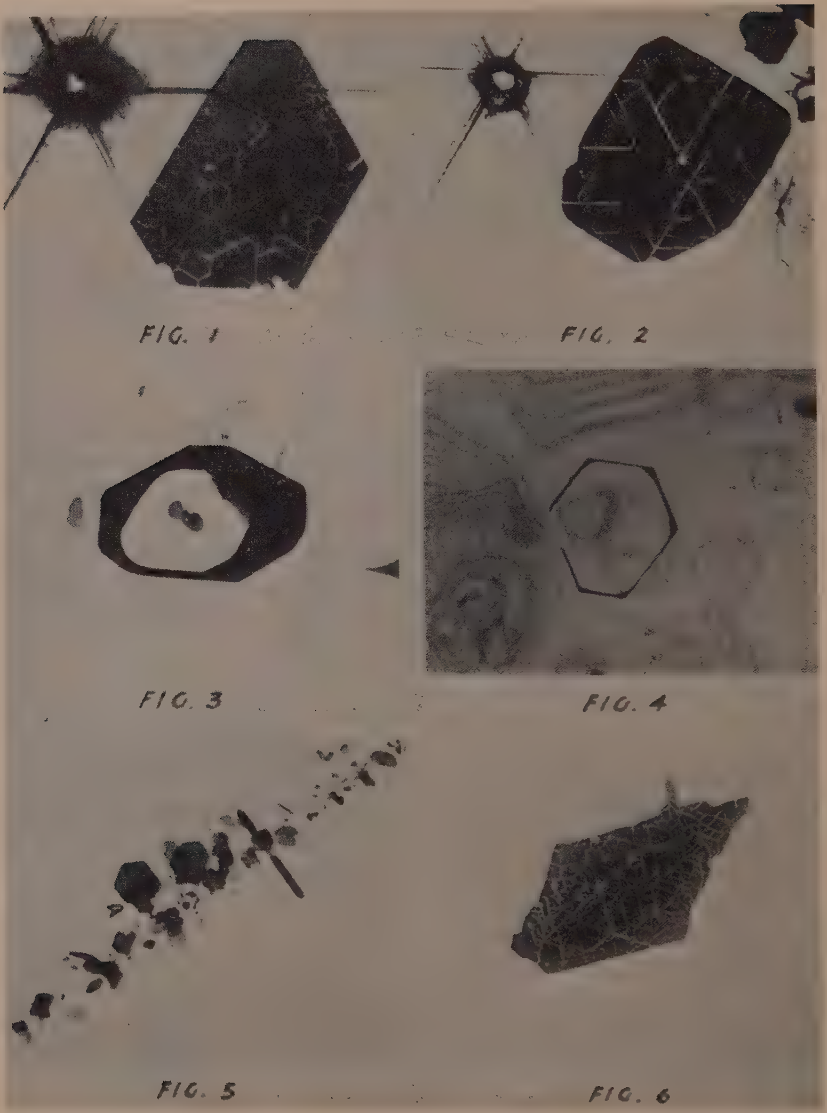

PLATE 1

FIG. 1. Magnetite inclusion of typical habit. The crystal is oriented with the parting cracks perpendicular to the rays of the percussion figure (i.e., parallel to the pressure figure). N. Y. C. ×24.

FIG. 2. Inclusion of unusual cubic habit, caused by the unequal development of truncating modifying faces. The crystal is oriented with the parting cracks parallel to the rays of the percussion figure. N. Y. C. ×24.

frequent occurrence on magnetite is the octahedron.[1] The crystals, as a whole, are combinations of (110) and (111), since the surface forming the contact with (001) of the mica, and on which the crystals are flattened, is an octahedral face, as has been noted. Modifying faces, truncating the angles of the dodecahedral outline, are occasionally present. The faces of the modifying forms are often unequally developed, and one or more of them may be entirely suppressed (Figs. 2, 3).

The unmodified dodecahedral crystals are frequently distorted by the complete or partial suppression of faces, and may then present triangular, trapezoidal or rhombic outlines. The outline is sometimes slightly rounded, more frequently in the thinner crystals, and in some instances the entire outline may be a smooth curve. Rarely the outline is partially or completely jagged.

Lath- and needle-like magnetite inclusions were abundant in muscovite from Gilsum, N. H. (Fig. 9), and were occasionally noted in specimens from other localities (Fig. 5). The needles show a single set of parting cracks, which are perpendicular to the direction of elongation. The lath-like inclusions, and locally enlarged portions of the needles, however, present all three sets of cracks. The terminations of the laths and needles are usually rounded, but may be rectangular, through the suppression of two adjoining dodecahedral faces in combination with a truncating face (Fig. 8). Rarely the terminations are formed by the ordinary dodecahedral faces, or by combinations of this form with modifying faces. In one instance, the lath-like crystals were observed to radiate from a common center (Fig. 8). A few bent needles were also seen.

Skeletal crystals are not uncommon, and present a variety of shapes. Several perfectly formed skeletal hexagons with reinforced corners were noted (Fig. 4). Other related crystals had a narrow, opaque border and a thin, translucent interior (Fig. 3). In phlogopite crystals from North Burgess, Ontario, translucent magnetite laths were marked by opaque

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[1] The persistence-values for the commoner forms of magnetite are (Chudoba, K., and Schilly, W., *Neues Jahrb., Beil.-Bd.* **68A**, pp. 241–267, 1934):

Form—111	110	100	331	511	531	211	510	331	432	773
p.v. — *89*	*79*	*69.5*	*54*	*21*	*17*	*16*	*14.5*	*14.5*	*6*	*6*

FIG. 3. Modified and distorted magnetite inclusion with a dark, thick, border zone and a thin, nearly transparent, interior. The "islands" are separate inclusions at different levels in the mica. N. Y. C. ×24.

FIG. 4. Hexagonal, rim-like, skeletal magnetite crystal with reinforced corners. ×24.

FIG. 5. Linear arrangement of magnetite inclusions. A lath-like crystal and two needle-like crystals can be seen. N. Y. C. ×24.

FIG. 6. Magnetite crystal with dodecahedral (?) parting. This parting is seen as two closely parallel cracks and a single inclined crack near the top of the photograph. N. Y. C. ×24.

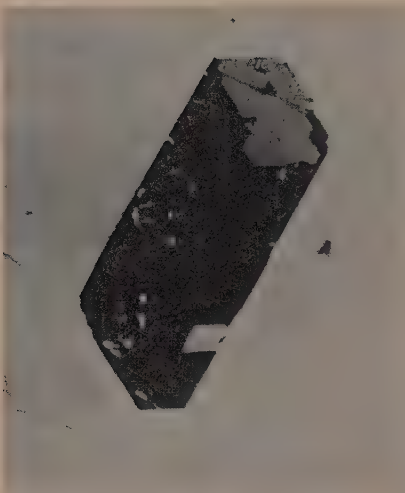

FIG. 7

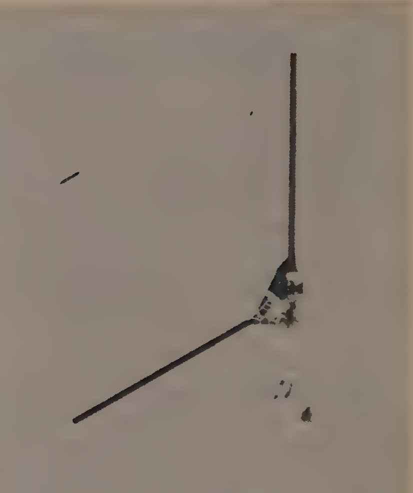

FIG 8

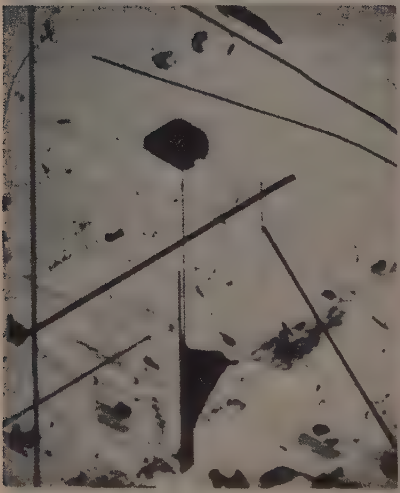

FIG. 9

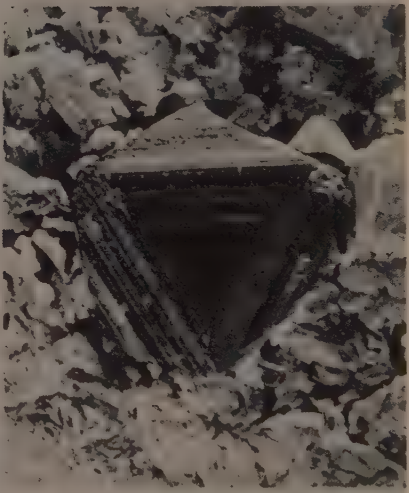

FIG. 10

PLATE 2

FIG. 7. Inclusion of typical habit, exhibiting layer growth. The thinnest layer, indistinct in the photograph, is found in the rhombic inserted area and in the small interior openings. The uncracked, opaque, irregular areas are pyrite. N. Y. C. ×28.

FIG. 8. Lath-like inclusions diverging at 120° from a common center. The terminations of the laths are rectangular. N. Y. C. ×28.

FIG. 9. Elongated lath- and needle-like magnetite inclusions. One lath is enlarged laterally. Six different orientations can be seen. Gilsum, N. H. ×18.

FIG. 10. Magnetite octahedron with pronounced growth terraces on the octahedral faces. Nordmark, Sweden. ×3.

lines along their margins while their interiors contained rounded openings, resembling bubbles in a tube. Three-dimensional skeletal magnetite crystals have been described from igneous rocks (18), glass (19) and sintered iron ores (20).

The magnetite inclusions are quite small, averaging 1 mm. or less in diameter. The largest equant crystal noted measured only 4 mm. in diameter. The small size and sporadic occurrence of the crystals makes them inconspicuous. The elongated crystals usually range between 0.05–0.1 mm. in width and 1–10 mm. in length. The average length of 766 such crystals was 5.3 mm. (Table 1). A few needles, although invisible or nearly so to the unaided eye, were found to range between 5 and 10 cms. in length.

Layer Growth; Interference Effects; Thickness. The thickening, or growth perpendicular to the plane of flattening, of the magnetite crystals is frequently seen to have taken place discontinuously by the deposition of successive layers of uniform thickness (Figs. 3, 5, 7). A single crystal may show three or four such layers. The boundary of each deposit may be irregular or straight, but is marked by an abrupt change in color. The layers do not spread out from a point in the interior of the underlying layer, but appear to grow inward from the sides of the crystal, as is suggested by the bordered and skeletal crystals previously described. Opaque areas of pyrite, free from parting cracks, may be present in the inclusions and be confused with the growth layers.

The layer growth may be related to the relatively thick growth terraces, built up parallel to (111) on macroscopic magnetite crystals (Fig. 10). Layer growth, similar to that of the inclusions, has been described for various organic and metallic crystals.

Small areas adjacent to the boundary of overlapping layers are sometimes brightly colored in shades of blue or blue-green in ordinary transmitted light. This interference phenomenon is possibly caused by extremely thin laminae of mica partially intercalated between the magnetite layers. No interference colors were observed from the inclusions themselves. Brilliant interference colors were observed over an area of overlap of separate, translucent magnetite crystals lying at slightly different levels in the mica.

The opaque inclusions transect the mica laminae, and range in thickness up to 0.5 mm. Crystals thicker than 0.05 mm. are rare, and usually form striated, lens-like bodies. The translucent inclusions are too thin and adherent to be mechanically separated from the mica. The limit of opacity could not be determined exactly, but is at a thickness of less than 0.003 mm., since mica sheets that thick containing opaque inclusions were prepared by cleavage. Cleavage sheets 0.001 mm. thick containing translucent, but relatively dark colored, needles were also prepared.

Orientation. The orientation of the inclusions to the mica can be defined by stating the position of a direction in the plane of flattening—(111)—of the magnetite relative to the direction 010 (or any other direction) in (001) of the muscovite.

It is necessary that the identity of a single, fixed, direction in the magnetite be known, in order that the full range of possible orientations on (001) may be traversed. In inclusions of equant habit, however, the only directions whose positions are known are those of the octahedral parting cracks, and the hexagonal symmetry of the cracks restricts the range of measurement to 30°. On this basis, the inclusions were found, almost without exception, to occur in two orientations: the parting cracks falling parallel either to the rays of the percussion figure (i.e., to 010, 110, and $1\bar{1}0$), or to the rays of the pressure figure (i.e., to 100, 130, and $1\bar{3}0$) of the mica (Figs. 1, 2). These orientations are ambiguous, inasmuch as (001) of muscovite actually possesses binary symmetry and is only pseudo-hexagonal, and hence the inclusions may be individually oriented to particular rays of one or the other of the figures. The percussion figure orientation is, on the whole, more frequent than the pressure figure orientation. There is a variation in this respect in specimens from different localities, and in different specimens from the same locality.

In the case of elongated inclusions, the entire range of possible orientations can be traversed by investigating the inclination of the direction of elongation to 010 of the muscovite, and the exact positions of orientation can be determined. The elongation, as has been noted, is parallel to a (110)–(111) edge, and is at right angles to the parting cracks. Measurements of 780 elongated inclusions in muscovite from Gilsum, N. H., established four different orientations, the direction of elongation coinciding with 010; 100; 110 and $1\bar{1}0$; and 130 and $1\bar{3}0$ of the muscovite (Table 1). Both the relative frequency of orientation and the relative elongation of the inclusions varies with these positions, and the elongation increases with the frequency of orientation. The percussion and pressure figure positions of the equant inclusions represent these four orientations.

Origin. The magnetite inclusions may be observed, when sufficiently abundant, to be arranged in successive, concentric zones outlining the growth stages of the mica. A partial, chevron-like, zonal arrangement or a simple alignment of the inclusions may also be noted (Fig. 5). Flattened inclusions of garnet and tourmaline are often associated with the magnetite inclusions and may then occur within and, when sufficiently abundant, be aligned within the magnetite zones. This mode of arrangement of the magnetite inclusions indicates that they have crystallized simultaneously with the mica.

TABLE 1. ORIENTATION OF ELONGATED MAGNETITE INCLUSIONS TO MUSCOVITE. GILSUM, N. H.

(The inclusions are flattened on (111), upon muscovite (001), and are elongated parallel to a (110)–(111) edge.)

Observed Inclinations to Muscovite 010.	0°	30°	60°	90°	Other
Corresponding Directions of Orientation.	010	130 $1\bar{3}0$	110 $1\bar{1}0$	100	
Number of Inclusions Observed.	23	507	29	207	14
Average Length in mm.	2.5	6.0	3.1	4.3	

The occurrence of thick, transecting, magnetite crystals also suggests a primary origin. Such inclusions could not have been formed by infiltration between the laminae, or by crystallization from solid solution. Furthermore, the inclusions do not appear to have originated by the chemical alteration of the muscovite, since they occur typically as widely separated individuals or, less often, in crowded aggregates in obviously unaltered, frequently colorless and transparent, mica books.

Localities. Magnitite inclusions were identified in muscovite from the following localities: Tuckahoe, Westchester County, New York; Gilsum, New Hampshire; Gilletts' Quarry, Haddam Neck, Connecticut; New Fane, Vermont; Spruce Pine, North Carolina; Fremont County, Colorado; Macon County, North Carolina; Standish, Maine; and 11 localities on Manhattan Island, New York City. Magnetite inclusions were also identified in phlogopite from North Burgess, Ontario, and New Connecticut, Jefferson County, New York, and in clinochlore from Tilly Foster, Putnam County, New York. Of the iron oxide inclusions in mica cited in the literature, only the instances described by Bowman ((1); Haddam, Conn.); Mügge ((12); India), G. M. Hall ((7); Spruce Pine, N. C.), and Lacroix ((9); France) definitely appear to be magnetite.

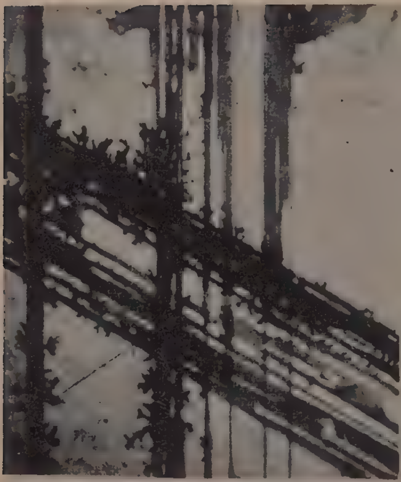

FIG. 11

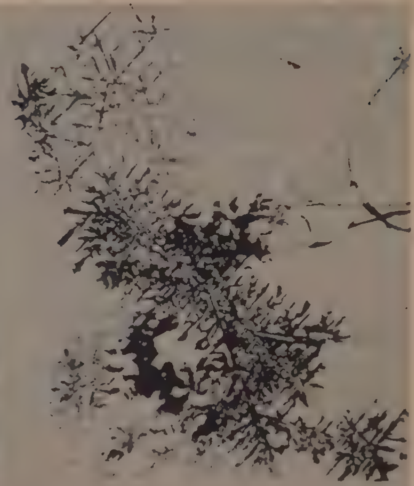

FIG. 12

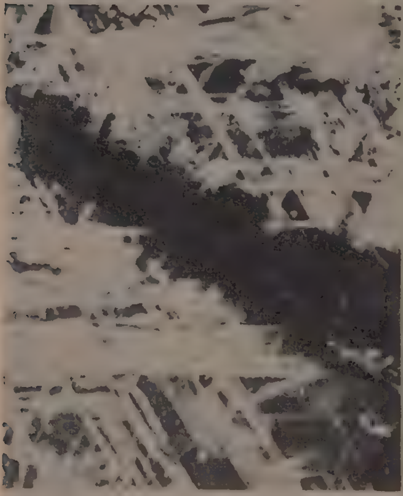

FIG. 13

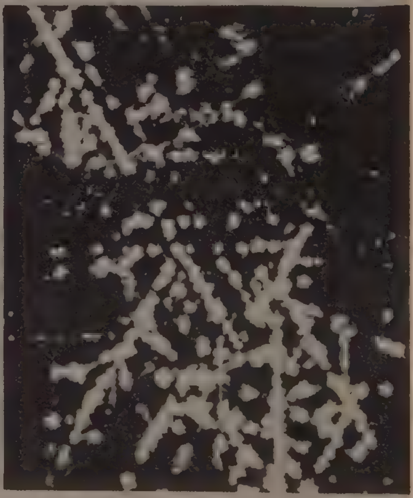

FIG 14

PLATE 3

FIG. 11. Lattice-like growths of hematite, showing minor dendrites springing from the sides of the laths. The two sets of laths are at different levels in the mica and are parts of separate crystals. Pennsbury, Pennsylvania. ×24.

FIG. 12. Extended dendritic growths of hematite. Three separate, overlapping, dendrites are present but cannot be distinguished in the photograph. The dendrites spring from long, narrow lattice rays, and their branches are severally oriented to the pressure and percussion figures. N. Y. C. ×10.

HEMATITE INCLUSIONS

A second type of iron oxide inclusion in muscovite appears as complex dendritic or lattice-like growths of relatively large size. Growths of this type are of wide-spread occurrence, and comprise most of the instances mentioned in the literature. Although the included mineral has generally been called magnetite, the growths differ markedly from the magnetite inclusions described on the preceding pages and undoubtedly represent some other mineral.

The color of the inclusions in transmitted light varies with their thickness from reddish brown and deep brown to pale brown and smoky tints. Opaque crystals are relatively rare, and are dull in luster and brownish black, reddish brown or deep brown in color. The translucent crystals are isotropic and non-pleochroic. Most of the inclusions that appear opaque to the unaided eye are subtranslucent when strongly illuminated under the microscope. Bright shades of yellow and red are seen in inclusions that have undergone alteration, presumably to hydrous iron oxides.

Habit; Size. The growths appear as an arrangement of laths or stripes intersecting in a lattice pattern at angles of 60° (Figs. 11, 13, 17, 18), or as dendrites with the arms branching at 60° (Figs. 12, 14, 15, 16, 18). All gradations occur between the lattice and dendritic varieties. The growths are usually extremely complex, and present a fascinating variety of patterns.

Sometimes one or two of the three sets of laths in the lattice growths are subordinate in development, or are suppressed altogether. Minute dendrites frequently spring from the major laths of the pattern (Fig. 11). Linear arrangements of seemingly isolated dendrites are found to be connected by extremely narrow rays usually visible only under magnification (Fig. 14). The marginal and aligned dendrites are apparently of later formation than the lattice rays from which they spring. Isolated dendritic cyrstals are also common, and a mica sheet may be closely speckled with small growths of this kind (Fig. 15). Single dendrites are frequently very complex, but may be simple star-like crystals.

The continued growth and filling-in of dendritic crystals eventually results in the formation of small, complete crystals with a hexagonal outline. Such crystals typically have a perforate or sieve-like appearance.

FIG. 13. Photogram of lattice-like growths of hematite. The inclusions are absent from a pressure zone that traverses the mica. A number of separate, overlapping crystals are present. Delaware. Natural size.

FIG. 14. Photogram of dendritic hematite growths aligned along indistinct, thread-like, lattice rays. The inclusion is almost entirely composed of a single, highly skeletonized crystal. Colorado. Natural size.

The rays of the lattice growths may also be bounded by hexagonal faces; however, the terminations of the laths are rarely well developed, and generally fray out into parallel needles. The sides of the dendrites are usually irregular. Occasionally the inclusions are neither dendritic nor lattice-like, but form broad equant crystals, 1 cm. or more in diameter, with a more or less perfect hexagonal outline. Such crystals grade by elongation into lath-like crystals. Small dendrites may spring from the corners of the hexagons.

Even the most extended and open lattice growths consist of a single highly skeletonized crystal. This fact is more apparent in the dendritic variety of inclusion. Ordinarily a number—sometimes hundreds—of such crystals occur at different levels within the mica sheet, and careful examination is necessary to trace out the extent of a single individual. Some of the instances of extended two-dimensional skeletal growth and distortion seen in the inclusions are remarkable. In muscovite from Fremont County, Colorado, very thin lattice rays had a width of 0.05 mm. or so and lengths up to 13 cms. These rays branched at one or both terminations into radiating rays of comparable dimensions, the whole assemblage representing a single continuous crystal. The stripes in the Pennsbury, Pennsylvania, muscovite occasionally measure 30 cms. or more in length. Lattice growths covering an area of 100 sq. cms. or more are very common, and the average size is, at least, several square centimeters. The dendritic growths are much smaller in area, and run on the average between 0.25 and 1 sq. mm., although they occasionally reach an area of 1 sq. cm. or more.

Parting cracks were not observed in any of the inclusions. In specimens from several localities, the growths were noted to contain minute dash-like inclusions, oriented in a 60° pattern, of a pink or colorless, birefringent mineral, probably rutile (Fig. 16).

Interference Effects; Thickness. Both the opaque and the translucent inclusions may be outlined on the surface of cleavage sheets by interference colors. The order of the color is not related to the thickness of the inclusions, and in very thin cleavage sheets the color may be seen to be different on opposite sides of an inclusion. The colors are not complementary. The effect is apparently caused by interference from a mica film above inclusions that are immediately adjacent to the surface of the sheet.

Interference colors may also be shown by relatively light colored inclusions not adjacent to the surface of the sheet, and are evidently produced by the inclusions themselves. The thickness of such crystals can be estimated from the color exhibited, and was found to range between

150 and 400$\mu\mu$. At greater thicknesses the interference colors are obscured by the absorption color. The thickness of the non-interfering, darker colored inclusions was estimated by measuring the thickness of the enclosing mica laminae, and was found to range below 0.006 mm. for even the thickest opaque crystals. The degree of transparency is greater than in the magnetite inclusions. The inclusions cannot be mechanically separated from the mica.

Identity of the Included Mineral. The lattice-like and dendritic growths from Pennsbury, which are characteristic of the type, were originally referred by J. D. Dana (3) to magnetite, but were later considered by Rose (14) to be hematite; Dana and Brush (4) later re-affirmed the view that the mineral was magnetite, and the growths have since been generally ascribed to that species. However, the inclusions contrast with the hitherto little known type of inclusion identified in the present study as magnetite, and undoubtedly represent some other species. The principal points of difference may be summed up as follows:

MAGNETITE	HEMATITE (?)
Color: in transmitted light typically lavender gray or pure gray; opaque crystals lustrous and iron-black.	*Color:* in transmitted light typically brown or smoky; opaque crystals dull and brownish black, reddish brown or deep brown.
Parting cracks, arranged in a 60° pattern.	No parting cracks.
Habit: equant hexagonal crystals; occasionally lath or needle-like crystals.	*Habit:* extended highly skeletonized dendritic and lattice-like growths, with hexagonal symmetry.
Size: equant crystals average 1 mm. or less in diameter; elongated crystals average 5 mm. in length.	*Size:* the lattice growths frequently are 100 sq. cms. or more in area, and average at least several square centimeters. The dendrites average about 0.25–1 sq. mm. in area but reach 1 sq. cm. or more, and are usually interconnected.
Opaque inclusions common; very thick (0.01–0.1 mm. or more) inclusions observed and transect mica laminae.	Opaque inclusions rare. All range in thickness below 0.006 mm. The degree of transparency is greater than in the magnetite inclusions.
Layer growth.	No layer growth.
Isotropic.	Isotropic; but, if hematite, the crystals are flattened on (0001) perpendicular to the optic axis.

Relatively rare; usually isolated, inconspicuous crystals.	Very common; usually densely aggregated, conspicuous crystals.
Origin: enclosed during the primary growth of the mica.	*Origin:* secondary, and apparently exsolution growths.

It is also significant that both the magnetite and the lattice and dendritic type of inclusion frequently occur together in the same mica sheet.

The absorption colors of the lattice and dendritic growths are charteristic of hematite, and it seems probable, since the mineral is known to be an anhydrous oxide of iron, that the growths represent this species.

Orientation. If the mineral of the inclusions is hematite, considerations of crystallographic coincidence with the muscovite, to be described, identify the plane of flattening as (0001). The isotropism and the hexagonal outline of the inclusions agree with this orientation.

The laterally bounding faces of the inclusions are not determinable. For instance, there are no means of determining whether the faces are of first or second order forms. However, certain features of orientation and coincidence with the mica, and the arrangement of the rutile (?) inclusions,[2] indicate that the laterally bounding faces are those of a first order form.

Lewis (10) was first to recognize that the inclusions stand in crystallographic relation to the muscovite. The symmetrical 60° pattern of the dendritic growths had earlier been ascribed by J. D. Dana (3) to repeated twinning.

Two general types of orientation can be recognized. The inclusions are commonly arranged with the directions of elongation parallel to the rays of the percussion figure. Rarely are the inclusions oriented to the pressure figure. As was noted for the equant magnetite inclusions, the orientations as stated in this manner are ambiguous.

Single crystal lattices and dendrites oriented to one of the figures usually have minor extensions, at right angles to the major system, oriented parallel to the other figure (Fig. 17). Small dendrites springing from the major laths of a lattice are commonly oriented in such fashion. In some case, a rectangular, grid-iron, pattern is formed by the equal development of rays of both orientations in a single growth. Occasionally elongated thread- or lath-like extensions from the growths traverse the mica at an angle to the pressure and percussion figure positions.

Origin. The origin of the inclusions is uncertain. However, certain features indicate that the hematite was not included during the primary

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[2] In the oriented overgrowths of rutile upon (0001) of hematite (11), the rutile is flattened on (100) and is arranged with *c* perpendicular to the $(10\bar{1}0)$–(0001) edges. If this orientation holds true of the rutile needles in the hematite inclusions, the bounding faces are those of a first order form, since the needles are arranged perpendicular to the outline.

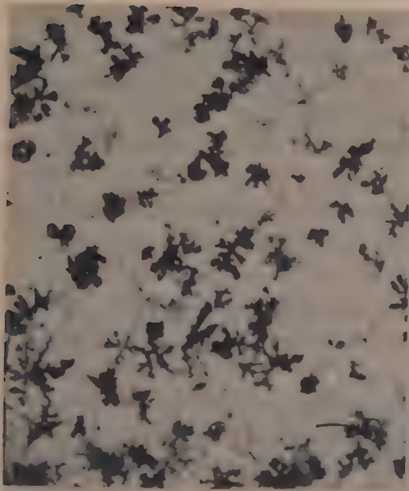

FIG. 15

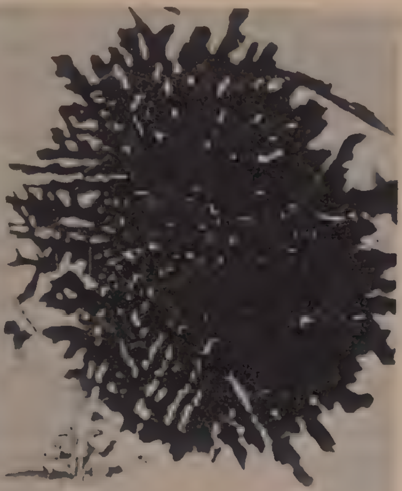

FIG. 16

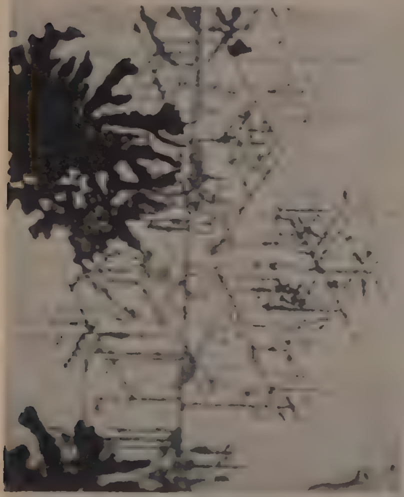

FIG. 17

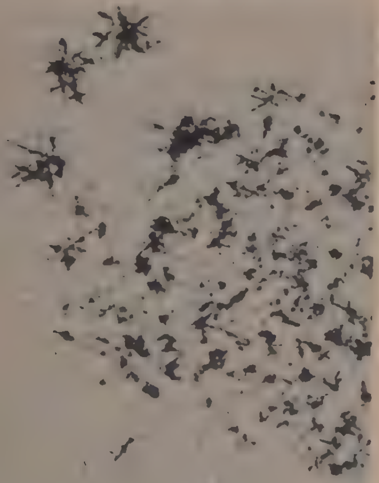

FIG. 18

PLATE 4

FIG. 15. Isolated dendrites of hematite. A portion of a large evenly spotted mica sheet. Colorado. ×14.

FIG. 16. A partially "filled-in" dendritic growth of hematite. Minute dash-like inclusions of rutile (*), oriented in a 60° pattern at right angles to the bounding faces, can be seen. N. Y. C. ×10.

growth of the muscovite. In wrinkled and sheared mica, for instance, the inclusions frequently occur in densely aggregated zones parallel to the wrinkling or ruling, and may be more or less confined to the disturbed areas of the books. Conversely, instances were observed in which the inclusions were absent from a pressure zone that traversed an otherwise undisturbed sheet of mica (Fig. 13).

In muscovite from Bedford, N. Y., the wrinkled and ruled portions of the sheets contained densely aggregated minute dendrites, interconnected by nearly invisible thread-like rays, while the undisturbed portions of the sheets contained scattered, broad, and more or less perfect hexagonal crystals 1 cm. or so in diameter. In many specimens from this occurrence the dendrites were aligned along parallel rulings in the mica. When the rulings were curved or slightly divergent, the hematite zones followed the curvature but the inclusions within the zones maintained their parallel orientation. The rulings were not open cracks, but sharp folds.

Inasmuch as the distribution and habit of the inclusions is influenced by secondary structures in the mica, the hematite must have originated subsequently to the crystallization of the muscovite. Other observers have also held the growths to be secondary. Nevertheless, the inclusions do not appear to have been formed by the chemical decomposition of the muscovite, as has been often suggested, or to have been emplaced by infiltration between the mica laminae.

The marginal portions of the sheets are characteristically quite free from inclusions, and the inclusions neither extend out from open, secondary cracks in the mica, nor occur within such cracks. Further, the inclusions are not more abundant in dark-colored, iron-rich, varieties of muscovite, as would be expected if formed by alteration, and commonly occur in colorless and unquestionably fresh and unaltered mica. The growths were found on a cursory examination to be rare in biotite and phlogopite. A few specimens of lepidolite and of chlorites and hydrous micas were also examined but no inclusions were observed. The widespread occurrence of the inclusions, the chemical stability of muscovite, and the occurrence of hundreds of closely interleaved inclusions in a single mica book also weigh against an origin by infiltration or by decomposition of the muscovite.

Fig. 17. A complicated single crystal lattice-work springing at right angles from a long lath-like ray. The two dark dendrites are separate crystals at different levels in the mica. N. Y. C. ×28.

Fig. 18. Hematite growth resembling both the dendritic and lattice varieties. N. Y. C. ×24.

Alternatively, the hematite may have crystallized from solid solution in the muscovite. This origin seems most in accord with the feature of variation in distribution and habit with respect to mechanical effects in the mica. Hexagonal, basally flattened exsolution growths of hematite are well known in aventurine feldspar, magnetite, carnallite and other species. The formation of exsolution growths of hematite in magnetite is facilitated by relief of strain (19).

Localities. Hematite growths of the nature described were examined in muscovite from Chandler's Hollow, Delaware; Darlington, Delaware County, Pennsylvania; Branchville, Connecticut; "Maine"; Pennsbury, Chester County, Pennsylvania; Fremont County, Colorado; Bedford, Westchester County, New York; "Quebec"; "North Carolina"; "India"; "Siberia"; and from 19 localities on Manhattan Island, New York City (Ashby collection). Many further localities are cited in references 1–16. The inclusions are very much more common than the magnetite inclusions described in the preceding section.

STRUCTURAL RELATIONS OF MAGNETITE, HEMATITE, AND MUSCOVITE

Comparison of the crystal structure of magnetite[3] with that of (001) planes of muscovite reveals a close similarity of atomic arrangement and spacing in (111) planes and a general dissimilarity in other planes. In Figs. 19*a* and 19*b* (111) oxygen planes of magnetite are shown superposed on a (001) oxygen plane of muscovite with the parting cracks in the percussion and pressure figure orientations. A close correspondence also occurs between (111) Fe″ and Fe‴ planes of magnetite and (001) Si (=3 Si+Al) planes of muscovite, but the overall coincidence is less than in oxygen planes.

With hematite, a close similarity of structure with (001) of muscovite occurs in (0001) planes. Lacroix (9) observed specularite crystals overgrowing muscovite in oriented position by sharing of these planes. In Figs. 19*c* and 19*d*, (0001) oxygen planes of hematite are shown superposed on a (001) oxygen plane of muscovite. The crystal outline is chosen as a first order form, and is drawn in the percussion and pressure figure orientations. On this basis, the greatest coincidence occurs in the percussion figure orientation, which is the most common position of the natural growths. A second order outline would place the greatest coincidence in the pressure figure orientation. The assumption as to habit, supported as it is by the arrangement of the rutile (?) inclusions, there-

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[3] Magnetite, $a_0=8.37$; hematite, $a_0=5.42$, $\alpha=55°\ 17'$; muscovite, $a_0=5.18$, $b_0=9.02$.

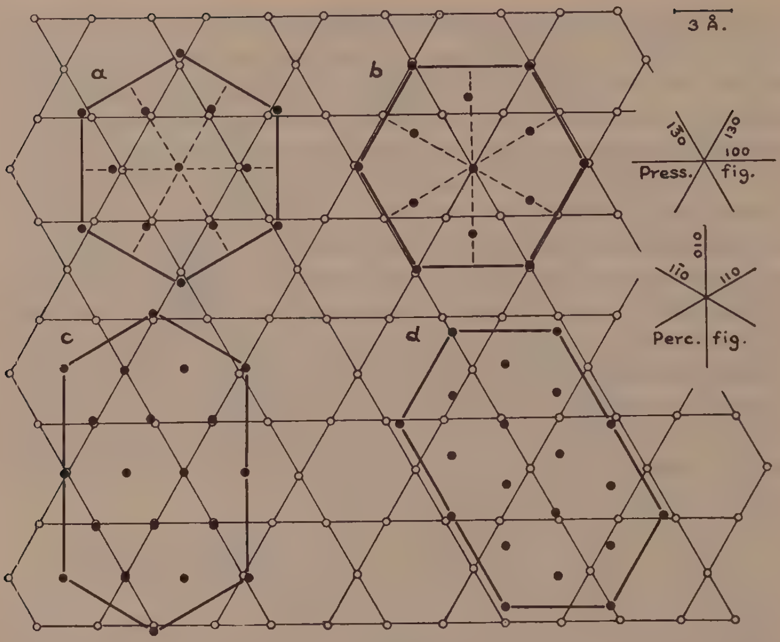

FIG. 19

Figs. 19*a* and 19*b* represent (111) oxygen planes of magnetite superposed on a (001) oxygen plane of muscovite. The crystal outline is dodecahedral, with the parting cracks (indicated by broken lines) parallel to the pressure figure in *a* and to the percussion figure in *b*.

Figs. 19*c* and 19*d* represent (0001) oxygen planes of hematite. The crystal outline is taken as a first order form, and is parallel to the percussion figure in *c* and to the pressure figure in *d*.

fore seems to be justified. In Fe''' (0001) planes of hematite, the overall coincidence with (001) Si planes of muscovite is less in either orientation than in oxygen planes, and the greatest coincidence, under the assumption made as to habit, is in the pressure figure orientation.

It is interesting to note that hematite and magnetite reciprocally form oriented over- and inter-growths by the sharing of (001) and (111) planes, and that they are analogously oriented upon (001) of muscovite. In terms of crystal growth, the structurally similar planes afford a ready-made foundation layer for the deposition of succeeding planes of the over- or inter-growing crystal, and determine positions of orientation of high frequency.

Oriented growths of muscovite upon magnetite or hematite have not been described. However, chlorite has been described overgrowing the

(111) faces of magnetite in oriented position (21). Al-spinel has also been observed (22) to be penetrated by plates of mica disposed parallel to the octahedral faces of the crystal.

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HEAVY ACCESSORY MINERALS OF THE VAL VERDE TONALITE

Robert W. Wilson, *California Institute of Technology, Pasadena, California.*

Introduction

Study of the heavy accessory minerals of igneous rocks by means of concentration of the heavy fractions is a fairly recent development in the field of petrology. Originally, work of this type was intended as a means of demonstrating the parent rock from which heavy minerals of various sedimentary deposits had been derived. In this direction, investigations have been of undoubted value. More recently, various workers have advocated the use of accessory minerals of igneous rocks as a means of correlation of igneous intrusions. In many cases their use has yielded results apparently of positive value. However, data on the precision of this type of correlation are still being gathered, and studies concerned with accessory minerals and their variation are of some importance at present.

The construction of the Metropolitan Water District Aqueduct for Los Angeles County, California, has necessitated the drilling of long tunnels at various points en route from the Colorado River. One such tunnel situated approximately one mile south of Val Verde, California, passes through some seven miles of tonalite. This locality offers a very favorable opportunity for the study of accessory minerals, and their variation through a continuously exposed section of igneous rock. The present paper embodies the results of a study of the heavy accessories in the tonalite and their variation through about five miles of tunnel, which distance is the longest continuous exposure of the rock without significant faulting.

P. H. Dudley has published recently (17) an account of the geology of the Perris Block of Southern California. The area reported on by Dudley includes that discussed in the present paper. The reader is referred to this report for a statement of the general geology of the Val Verde district. However, no detailed study of the rocks near Val Verde was presented. E. F. Osborn of the California Institute of Technology is now engaged in a comprehensive petrographic survey of these rocks. He has kindly furnished the following description of the tonalite.

> The tonalite is a coarse-grained rock, medium dark in color, and varying only slightly in composition throughout the district. The rock contain 50 to 60% andesine, 15 to 30% quartz, and 15 to 30% biotite and hornblende, the biotite commonly being more abundant than hornblende. Occasionally a very small percentage of orthoclase is present. Magnetite, sphene, apatite, and zircon are the common accessory minerals.

A constant, conspicuous feature of the tonalite is the presence of abundant dark, fine-grained, rounded inclusions. These vary from a few inches to several feet in diameter, but the average is about one foot across. In a few places the inclusions are practically absent and in others occur in swarms making fifty per cent or more of the rock. In the latter instance they are more angular and more tabular in form and have a common orientation striking northwesterly and dipping steeply.

Preparation of Samples for Study

Samples of the tonalite were taken at approximately half-mile intervals in the Val Verde tunnel. In addition, a sample of one of the numerous inclusions was also studied. The specimen numbers represent hundreds of feet from an established bench mark at Parker Dam.

The collected samples were crushed and sieved and thirty grams of material between 100 and 150 mesh grade-size were taken for each determination. The sieved specimens were then panned to about one-half of their original weight. This operation served to eliminate much of the biotite along with the lighter minerals, and afforded a cleaner separation of "heavies" and "lights." Since rock flour was eliminated concurrently, the time consumed was not increased materially. The "heavy" minerals were next separated by the usual bromoform procedure. Electro-magnetic separation of the "heavy" crops into strongly magnetic, moderately magnetic, and non-magnetic fractions, and mounting of the non-magnetic portions completed preparation of the samples. Due to time limitations, and because the more important accessory minerals are usually non-magnetic, the strongly and moderately magnetic crops were given only cursory examination.

Accessory Minerals of the Val Verde Tonalite

The following accessory minerals were identified in the Val Verde tonalite: zircon, apatite, sphene, epidote, clinozoisite, zoisite, allanite?, tourmaline, monazite, anatase, calcite?, thulite?, and pyrite. In addition, several unidentified minerals were of sporadic occurrence. A complete list of "heavies" would include also hornblende, biotite, and magnetite.

The non-magnetic or weakly magnetic accessory minerals of the Val Verde tonalite may be placed in three categories:

(1) primary minerals, in a sufficient abundance to have been recorded in all specimens examined, and to be expected in any normal sample studied. Minerals: zircon, apatite, and sphene.

(2) secondary minerals, usually present in sufficient quantity to be expected in a random count. Minerals: epidote group, composed of epidote, clinozoisite, and zoisite (usually rare) in varying proportions.

(3) primary and secondary minerals sufficiently rare or absent in most samples that their presence in a particular sample cannot be predicted.

Minerals: tourmaline, monazite, anatase, calcite?, allanite?, thulite?, pyrite, and undetermined minerals. Monazite and more particularly tourmaline may have a range restricted to the higher-numbered samples but their rarity prevents a definite determination regarding their presence or absence.

Heavy Mineral Per Cent. The per cent. of heavy minerals obtained from the bromoform separation after preliminary panning of the specimens ranged from 5 to 11%. Sample No. 11937 was split and one fraction was separated into its "heavy" and "light" components without preliminary panning. The other fraction received standard treatment. Hence, comparison of the panned with the non-panned fractions of No. 11937 affords a means of roughly estimating the actual heavy mineral content of the tonalite specimens. Such an estimate suggests that the heavy mineral proportion (i.e., including biotite and hornblende) probably averages about 20% (between 10% and 25%).

Sphene apparently was the most abundant accessory mineral, although the effect of both panning and crushing may be to increase the number of grains of this mineral. Zircon was the least abundant mineral in group (1) except at the extreme western end of the tunnel, where it increased rapidly in amount, apparently with concomitant decrease of apatite. An average of panned samples gives zircon—17%; apatite—29%; and sphene—54%: or a ratio of zircon: apatite: sphene of about 2:3:5. A more normal ratio is probably 1:4:5. The table presents the results of the grain counts. Only the primary accessory minerals zircon, apatite, and sphene are recorded.

Notes on Individual Minerals

Zircon: occurred as colorless, well-crystallized, prismatic grains, generally with acute terminations. A few crystals, mostly encountered in specimen No. 11937, exhibited a faint zonal structure. The average zircon was not noticeably elongated, but such crystals occurred throughout the series of specimens examined. A number of the grains showed the effects of corrosion. Most of the zircons possessed a greater or lesser number of inclusions. These were either colorless and prismatic, possibly representing gas bubbles, or brownish to opaque inclusions of less regular shape.

Apatite: colorless or at times slightly yellowish grains, generally prismatic with rounded terminations. In some cases, the grains were terminated by crystal faces. Rarely, the apatite consisted of irregular fragments with no trace of crystal form. Inclusions were fairly common. Generally, they were of lower index than apatite. In some instances, the included material was zircon. Apatite showed a marked decrease in relative abundance in the extreme high-numbered samples (western end of tunnel) correlated with an increase of zircon at this point. This feature may point to a gradation toward a more acid rock type.

Sphene: generally found as irregular fragments without crystal faces, although in some specimens faces were present. A very few grains were essentially euhedral. The usually transparent grains ranged from colorless through pale yellow-green to yellow or yellow-brown. Inclusions were found in some individuals, and others appeared to be clouded by

Table of Zircon-Apatite-Sphene Percentages

Number	Panned from—to—(gms.)	% Heavies >2.86 s.g.	Total Zircon, Apatite, Sphene grains counted	Zircon		Apatite		Sphene		Crusher
				%	% error ±	%	% error ±	%	% error ±	
11730*† (not panned)	—	5	265	12	11.2	54	3.8	34	5.7	mortar
11755	30–12.1	7	621	5	12	41	3.5	54	2.5	mortar and Braun**
11779	60–20	9	451	12	8.5	39	4	19	3.5	mortar
11804	30–16.2	10	333	4	16.5	21	7	75	2.5	mortar and Braun
11829	30–18	5	317	9	11.5	23	6.5	67	2.5	mortar and C.I.T.††
11866	30–12.8	6	619	15	6.5	35	4	50	3	C.I.T.
11895	30–10.8	7	523	13	8	46	3	41	4	mortar
11914	30–13.1	11	398	19	6.5	25	6	56	3	mortar and Braun
11937† (not panned)	—	23	486	16	7.5	42	4	42	4	mortar
11937	49.9–17.2	9	390	23	6	31	5	46	3.5	mortar
11962	30–14.2	5	299	29	6.5	16	9.5	55	3.5	mortar and C.I.T.
11980	30–15.8	11	179	45	5.5	11	15	44	5.5	mortar and Braun
11742 (dark inclusion in tonalite)	30–15.6	27	488	14	7.5	83	<1.5	3	>13.5	Braun

* % error calculated; others from probability curves.

† Sample washed before weighing.

** Braun disc-crusher.

†† Calif. Inst. hand crusher.

the presence of minute inclusions. Some of the colored types were pleochroic in brownish tints. Color variation was irregular and appeared to bear no relation to the position of the sample. Cleavage, fracture and parting frequently combined to form a mosaic pattern. The per cent. of sphene was relatively constant throughout the section examined. However, it was noted that the method of crushing the rock sample had an influence on the number of grains of sphene appearing in the count (see the table).

Monazite: appeared usually as small, euhedral grains which were short, diamond-shaped prisms; typically clove-brown or yellowish to reddish-brown in color. There was no observable pleochroism. A few inclusions were sometimes present. The mineral was quite rare but was recorded in No. 11937, and one doubtful grain was encountered in No. 11914. Its presence in a tonalite is unusual and some grains suggested colored zircon. However, since certain crystals were so like monazite in character, the identification is justified. An alternative determination may be yellow zircon, but this variety is rare.

Tourmaline: ordinarily exhibited strong dark-blue or greenish-blue to very pale reddish-brown pleochroism. The mineral was light brown in ordinary transmitted light. The grains were generally prismatic without definite crystal form. Some of the grains were relatively pure, but fragments of tourmaline commonly exhibited a blotchy or hybrid appearance, sometimes either almost enclosing or intergrown with other minerals. Although, because of the small size of the fragments, origin of the tourmaline cannot be definitely established, this mineral may exist as a replacement of feldspar. However, there is no evidence that suggests the Val Verde tourmaline is post-consolidation. Perhaps, it should be considered a secondary mineral formed as the result of slight pre-consolidation autopneumatolysis.[1] Tourmaline was identified positively in only two samples (Nos. 11937, 11980). Unfortunately, the mineral was too scarce in the samples in which it was found to assume safely that it was absent in the others. However, since the per cent. of zircon increased at the point tourmaline made its appearance, tourmaline may be associated with increasing acidity of the rock mass, and may not have been present in the lower-numbered samples.

Epidote-Clinozoisite-Zoisite: doubtless epidote, clinozoisite, and zoisite are all present in the Val Verde tonalite. However, it was not possible always to distinguish between them, especially if the optic sign could not be determined. The Val Verde epidote was colorless as well as pistachio-green, and there were several examples of yellow or brown epidote as well. Altered grains comprising a mixture of epidote and feldspar indicated the derivation of the epidote minerals from the calcic feldspars. These altered grains were especially numerous in samples in the higher 11900's. The position of the specimens in the tunnel apparently had little influence on the abundance of epidote.

Abnormal Blue Anatase: intense blue or bluish-black grains were found in several of the samples. Their optical characters agreed with those shown by blue anatase except for low birefrigence and apparent biaxial positive optical character. Anatase is sometimes, but not invariably, a pneumatolytic mineral. Since its distribution in the Val Verde tonalite was somewhat comparable to that of tourmaline, its presence may have been due to to pneumatolytic action.

Allanite?: a number of dark brown to yellow grains, scattered throughout the series of specimens examined, appeared to represent the rare-earth mineral, allanite. This species, although probably present, was not an important member of the accessory mineral suite.

Thulite?: specimen No. 11980 yielded one grain of a pleochroic mineral which may represent the manganese zoisite, thulite.

Pyrite: several samples showed infrequent grains of an opaque, yellowish (non-magnetic?) mineral apparently representing pyrite. Some of the grains were coated with a red decomposition product (hematite).

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[1] Regarding the use of the term secondary in reference to preconsolidation minerals see 10, pp. 321–322, 329–330.

Calcite?: calcite or a related carbonate was of sporadic and extremely rare occurrence in the Val Verde tonalite.

High Index Mica: a micaceous mineral with index of refraction about 1.70 was recorded from the tonalite. Relatively rare, it was probably most abundant in the inclusion sample studied.

Undetermined Minerals: several undetermined minerals were present in the samples. They were of too infrequent occurrence to be of much importance.

As mentioned previously, hornblende and biotite formed the bulk of the heavy minerals. The extremely magnetic crops of the samples yielded magnetite, and a red iron oxide apparently derived from altered biotite.

Sources of Variation of the Accessory Minerals

It is to be noted from the percentages expressed in the table (and in the other minerals not listed) that some variation exists in the frequency of occurrence of the accessory minerals of the Val Verde tonalite. Since part of this variation is not due to changes in composition of the tonalite, it is pertinent to consider the possible sources of variation observed in the grain counts made during the course of the work.

Variation may be introduced by lack of absolute control during preparation of the samples for study. A certain amount of fluctuation cannot be avoided in either the bromoform separation or the subsequent electromagnetic separation. Moreover, in regard to the latter factor, the presence of a large amount of lamellar biotite and hornblende apparently served to carry, during separation, non-magnetic minerals into the magnetic crops. The flat, relatively large surface area of the grains perhaps accounts for this phenomenon.

Panning appeared to eliminate apatite at a faster rate than either zircon and sphene so that the relative amount of apatite was reduced. Doubtless in the present instance, the relative decrease of apatite is caused chiefly by the lower specific gravity of this mineral as compared to sphene and zircon. However, if attention is confined to the panned samples, although apatite may be reduced in an absolute sense, the variation of apatite from one sample to another will be a measure of actual conditions in the rock mass.

Sphene was generally present as irregular grains without much trace of original crystal form. Since in many cases the grains were traversed by a network of fracture, parting and cleavage cracks, it was suspected that during the course of crushing, a single grain of sphene might break into several. If attention is given to the table wherein are listed the percentages of zircon, apatite, and sphene in regard to each other, it will be seen that the type of crusher used has affected the apparent abundance of sphene. Crushing by a Braun disc-crusher or a large mill-stone type designated as the California Institute crusher in the table, resulted in the formation of a larger number of grains than in specimens where a relatively light mortar and pestle was used. For this reason, comparisons of the zircon-apatite-sphene ratios should be confined to panned samples which were crushed on either the Braun or mill-stone types.

Errors in identification are another source of variation in grain counts. In the present instance, at least insofar as the minerals of the table are concerned, errors arising through misidentification can have only a negligible effect on the results.

An important source of variation is the strictly mathematical one of error introduced because only a limited number of grains are counted for each specimen. The accuracy of the counts increases as the square-root of the total number of grains counted. The counts in the present work averaged between 300–400 grains of the primary accessories zircon, apatite, and sphene. The table gives the probable per cent. error, plus or minus, in each per cent. for the Val Verde samples. Data for the probable error were taken from an article by A. Lincoln Dryden Jr. (16). As may be seen from the table, this factor affects chiefly the minerals present in small amounts.

Lastly, variation in frequency of mineral occurrence may be due to actual changes in the constitution of the rock. Considering the deviation which is introduced by other means, it is difficult to reach an unequivocal determination of such variation. However, the Val Verde tonalite exhibited a certain directional change which it seems reasonable to attribute to actual diversification in the rock.

Mineralogical Variation in the Val Verde Tonalite

Notwithstanding a considerable amount of variation in the accessory minerals of the Val Verde tonalite, the composition is as homogeneous as could be reasonably expected in an igneous mass as large as that surveyed. The accessory mineral suite remained limited in number of species throughout the portion examined, and was uniformly characterized by a high per cent. of sphene. Ratios of zircon to apatite were variable, but the variation was gradual and directional. Generally, apatite was much more abundant than zircon, and if variations due to panning and crushing were eliminated, apatite in most cases would be quite comparable to sphene in abundance. The only other accessory minerals which were ever common were the secondary minerals of the epidote group. Other minerals which were present occasionally were always very limited in amount. Hence, the present study serves to bear out the view that in a homogeneous rock mass the accessory minerals remain fairly constant and distinctive.

The only variation in composition which appeared to be important suggested the thesis that the rock is more acidic at the western end of the tunnel than at the eastern end. Thus, in the higher-numbered samples there was an increase in zircon and a decrease in apatite. At the same time there was an introduction of tourmaline, monazite, and anatase. An increase in the degree of corrosion of zircon was also noted at this point. The average length of zircon crystals may have been somewhat greater although this is open to question. It should be stressed that the samples studied were typical specimens of the Val Verde tonalite. These more acidic-appearing samples were not dike rocks or similar types. An explanation may be furnished by the fact that the tonalite is closer, at this point, to overlying and intruded schists, and hence to the margin of the batholith.

Val Verde Inclusions

Inclusions are fairly numerous in the Val Verde tonalite. A description of their appearance has already been given.

A sample of one of these inclusions (No. 11742) was studied and proved to be quite distinctive when compared to normal specimens of the tonalite. The per cent. of heavy minerals was almost double that of the ordinary Val Verde specimens. Apatite was the chief accessory mineral present. Sphene was extremely rare. The per cent. of zircon was similar to that of normal specimens but the grains were considerably broken and fractured. Perfect euhedral crystals were not as abundant as in other samples, and many of the grains showed marked corrosion. Another point was the extreme scarcity of epidote and zoisite in the sample. The inclusion occurred at a place in the tunnel in which epidote was very common.

A study of the accessory minerals of No. 11742 indicated the intrusion of the tonalite into a rather basic type of rock, and the stoping or breaking off of fragments of the rock to furnish the material of the inclusions.

Percentage Representation of Minerals

After some consideration it was decided to restrict the calculation of percentages to the primary minerals zircon, apatite, and sphene. Neither the secondary minerals of the epidote group, nor the primary minerals of rare occurrence are of much importance in a study of the constancy of accessory minerals in the Val Verde tonalite. Attention is directed generally toward the relatively abundant primary accessories.

Representing mineral frequency of occurrence in per cent. has certain objections which have been pointed out by several workers. W. M. Cogen (13, p. 5) has recently reviewed the chief objections to percentage representation. By limiting the calculations in the present instance most of the objections are not serious. Since sphene remained fairly constant, the apparent increase of either apatite or zircon was essentially real. Unfortunately, with the data as given in the table, a general increase of all three minerals cannot be detected. If the per cent. of these minerals to the total heavy fraction could be determined this would not be the case. However, some of the non-magnetic samples were so small that the entire specimen was mounted for counting. Others possessed many times this amount but the samples were always too small to make use of a miniature sample splitter or other device without serious danger of losing most of the crop. Hence, this per cent. could not be determined with any reasonable accuracy.

Conclusions

1. The Val Verde tonalite possesses a relatively limited suite of minerals of fairly constant frequency.
2. High-numbered samples at the western end of the Val Verde tunnel point to the existence of a more acid phase of the tonalite in this region.
3. The accessory minerals are sufficiently uniform and characteristic to suggest their use in correlation.

Since the work was confined to the study of accessories from a single rock type of quite homogeneous aspect, it is perhaps not demonstrated that the minerals are adequately distinctive for correlation criteria. Apatite, sphene, and zircon are very common in many and varied rocks. However, the present study indicated a constancy in the accessory minerals which intimates that distinctive comparisons with other rocks can be made. The inclusion sample studied was certainly quite discriminative. At least, it may be stated that the Val Verde tonalite accessories do not vary sufficiently to demonstrate in themselves that correlation is not possible.

Acknowledgment

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Balch Graduate School of the Geological Sciences, California Institute of Technology. Contribution No. 208.

DEVELOPMENT OF QUARTZ PORPHYROBLASTS IN A SILICEOUS HORNFELS[1]

G. E. Goodspeed, *University of Washington, Seattle, Washington.*

Abstract

A siliceous hornfels in the Wallowa mountains of northeastern Oregon contains small quartz porphyroblasts. In thin section the porphyroblasts show several stages of development from initial forms which are barely distinguishable from the groundmass on account of the abundance of minute inclusions, to later forms which are gradually cleared of inclusions. Some of the porphyroblasts have euhedral boundaries yet consist of several individuals of varying optical orientation. Idiomorphic pyrite is contained in some of the quartz porphyroblasts. The petrographic evidence seems to indicate a facility of crystallization in environment which might not be expected to favor idiomorphism and may indicate an initial step in the recrystallization of the rock.

Occurrence

The hornfels described in this paper forms a part of a series of pre-Tertiary metamorphic rocks situated about one mile north of the mining town of Cornucopia on the southeastern flank of the rugged Wallowa mountains, one of the higher ranges of the Blue mountains group of northeastern Oregon. Although this region lacks detailed geologic maps, several papers have already been published. Of the earlier publications, that of Lindgren[2] in the 22nd Annual Report of the United States Geological survey is the most comprehensive. Recently Gilluly[3] has given an excellent summary of the general geology of the region. In the immediate vicinity of Cornucopia steep glaciated valleys afford excellent exposures, and considerable petrologic data has also been obtained through access to mine workings. Locally the metamorphic series is traversed by numerous irregular invasions of granodiorite. The hornfels occurs as steeply dipping bands, several feet in thickness, which have a northly trend and exhibit a parallel jointing in the same direction. One of the outstanding characteristics of the hornfels is an almost cherty appearance imparted to it by its siliceous composition and by its compactness, brittleness, and subconchoidal fracture. It is light to medium gray in color and may be liberally sprinkled with dark greenish spots, or may be nearly free from them. Small cubes of pyrite are visible with the aid of a hand lens and where oxidized they appear as brown specks, due to the oxidation of the pyrite. For this reason surface outcrops and joint cracks are somewhat stained with limonite.

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[1] Presented at the thirty-fourth meeting of the Cordilleran Section, Geological Society of America, Palo Alto, 1935.

[2] Lindgren, W., Gold belt of the Blue mountains of Oregon: *U. S. Geol. Survey, 22nd Annual Rep.*, Pt. **II,** pp. 561–776, 1900–1901.

[3] Gilluly, J., Reed, S. C., Park, C. F. Jr.: Some mining districts of eastern Oregon: *U. S. Geol. Survey, Bull.* **846A,** 1933.

Under the microscope the unspotted hornfels exhibits a cryptocrystalline groundmass which appears as a sutured interlocking aggregate of minute irregular anhedra of quartz, filled with inclusions which consist chiefly of very small flakes of a pale green slightly pleochroic mineral, probably a member of the chlorite group. Some of the sections show very minute isotropic grains which may be garnet, and a few grains of what is probably epidote. Most of the dust-like material in the groundmass is too fine to be determined. There are many minute opaque grains that suggest pyrite and some of these are oxidized to limonitic material. Quartz porphyroblasts are common in this variety of unspotted hornfels.

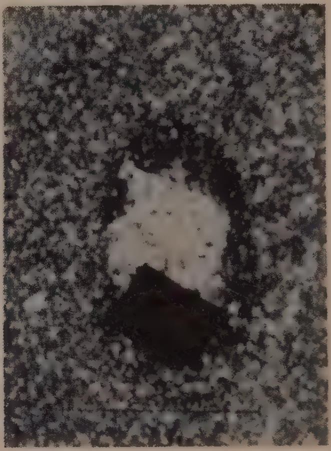

Fig. 1. Photomicrograph of a segregation spot and associated pyrite crystal. The outer zone of the spot shows a slight tendency to form a crystal face. Crossed nicols.

The spotted hornfels shows a profusion of small (about 0.5 mm.) dark greenish spots, covering from 10 to 30 per cent. of the rock. Under the microscope it is seen that these spots have a nucleus of a slightly coarser aggregate of quartz anhedra, surrounded by a wide ring containing a greater concentration of the same green flaky mineral of low birefringence, which is common in the groundmass of both varieties. The color and low birefringence suggests that it is one of the chlorites. Some of the spots contain small grains of pyrite and some are adjacent to large pyrite porphyroblasts (Fig. 1). Although most of these spots have a rounded or irregular outline, there are some which in shape suggest the expression of crystal faces of quartz while others are gradational into later forming quartz porphyroblasts (Figs. 1, 2*a*, 2*b*). In one section there are several quartz porphyroblasts in various stages of development from the segregation spots. The first step is a change in texture from a fine to a coarser grained mosaic. Then crystal faces begin to appear and the texture becomes still coarser until a compound porphyroblast is developed. In the final stage the porphyroblast is a single crystal.

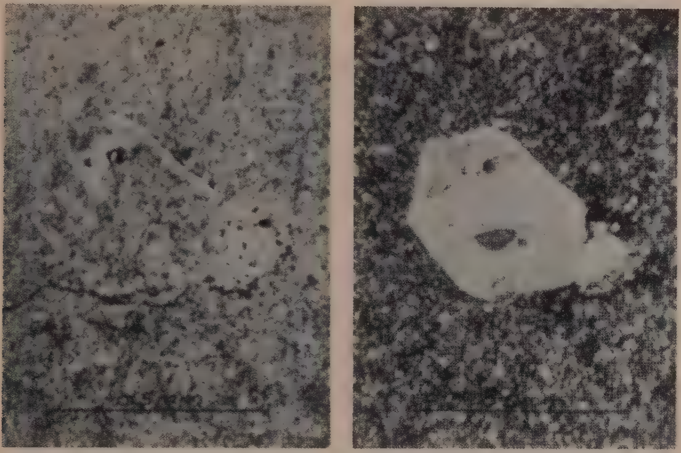

Fig. 2*a*
(Nicols not crossed)

Fig. 2*b*
(Crossed nicols)

The photomicrograph taken with uncrossed nicols shows that the minute inclusions common to the groundmass are distributed through the quartz porphyroblast. Under crossed nicols the crystal faces are clearly delineated. The quartz porphyroblast is associated with a segregation spot.

However, it is not certain that segregation in these spots always precedes the porphyroblasts in formation for there are many porphyroblasts quite independent of the spot-segregations, and with no indication that spots had ever formed. In some sections small initial porphyroblasts have apparently been formed by the coalescing of the minute interlocking anhedrons of the groundmass. Some of these porphyroblasts are irregular in outline while others, even when very small, show a tendency to develop a crystal outline.

Most of the quartz porphyroblasts are of small size, about 0.5 mm. in diameter. Some show prism and rhombohedron faces, some are distorted and others appear to be gradational with respect to either segregation spots or to the groundmass of the hornfels. Even though the prism faces may be unevenly developed trigonal symmetry is commonly noticeable.

Some of the porphyroblasts are difficult to distinguish in plane light, although they are readily discernible with crossed nicols (Figs. 2*a* and 2*b*, 3*a* and 3*b*). This difficulty of recognition is due to the fact that an abundance of minute inclusions of the groundmass extends through the quartz crystals. Other porphyroblasts do not contain as many inclusions, and in some a clearer outside rim is present. Euhedral pyrite crystals are associated with some of the porphyroblasts and are even found near the center of quartz crystals (Fig. 4).

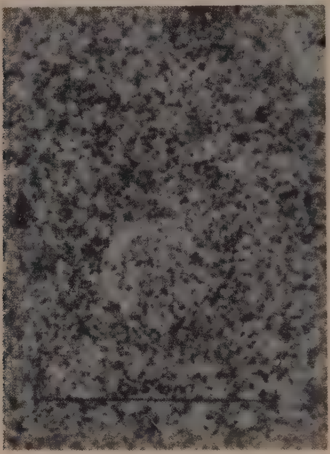

FIG. 3*a*
(Nicols not crossed)

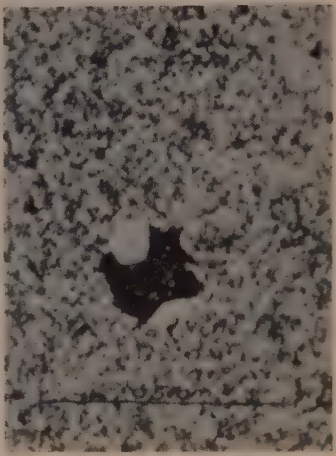

FIG. 3*b*
(Crossed nicols)

In the photomicrograph taken with uncrossed nicols the quartz porphyroblast is barely discernible while with crossed nicols the compound character of the crystal is evident.

Many of the quartz porphyroblasts are compound crystals, each individual having a different orientation and yet having certain faces in common (Fig. 3*b*). Under plane light a crystal may exhibit what appears to be a basal section of a single crystal, while with nicols crossed a compound crystal is evident.

In his discussion regarding the mechanism of crystal growth, Davey[4] states that if the strength of the crystal is in excess of the strength of the surface forces, the crystal will be polyhedral in shape, whereas if the strength of the crystal is less than that of the surface forces, it will have a rounded exterior. He is also of the opinion that if two crystals having different orientations meet in the body of a solid, there is at the interface a thin layer of molecules whose positions represent a compromise between the locations demanded by one of the crystals and those demanded by the other. As crystal growth occurs it is necessary for one of the crystals to align the molecules of this semi-disorganized intercrystalline layer according to the pattern set by its own orientation. Then a new intercrystalline layer would be formed at the expense of the less favorably oriented crystal. The molecules of this layer would then be aligned to conform to the pattern of the growing crystal and the cycle repeated until the less favorably oriented crystal disappears. Such a mechanism might offer an explanation for the irregular boundaries commonly present between differently oriented portions of a quartz porphyroblast.

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[4] Davey, W. P., *A study of crystal structure and its applications.* McGraw-Hill Book Co., **1934.**

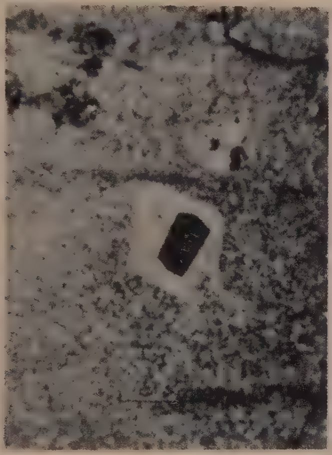

Fig. 4
(Nicols not crossed)

Photomicrograph showing irregular segregation spots and a subhedral quartz porphyroblast with an included crystal of pyrite. One of the faces of the quartz porphyroblast is gradational into the groundmass.

Conclusions

Quartz is usually placed near the end of the crystalloblastic series and most authors state that it rarely, if ever, forms euhedral crystals under conditions of recrystallization. Especially in a siliceous rock it might be expected that there would be many centers of crystallization for quartz, so that recrystallization would produce a mosaic texture. However, Tokarski[5] has noted idiomorphism in quartz developed in a sandstone which had been subjected to a "regeneration process." From the study of the porphyroblasts in this hornfels it is believed that idiomorphism occurs even under conditions which might be expected to be unfavorable for crystal growth. It is possible that these conditions have been changed by the gradual diffusion of volatiles through the rock, or by the local concentration of volatiles or solutions along minute fractures. The formation of the quartz crystals in this hornfels was crystalloblastic since growth took place in an essentially solid medium and the small inclusions of the groundmass were surrounded and included in the growing porphyroblasts. Then as crystallization proceeded, they cleared themselves of inclusions, perhaps in part, through the agency of crystallization pressure.[6]

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[5] Tokarski Juljan, Uwagi o Rosenbucha regule "Kolnosce crystalizacji mineralow w magmie" Kosmosu, Tom **50**, Zesz 1, 1925.

The fact that these porphyroblasts which contain crystals of pyrite are usually clearer, suggests that the iron sulphide has acted as a collecting agent (Fig. 4). The formation of pyrite gives evidence of volatiles or solutions while the trigonal symmetry of the quartz indicates a temperature of formation less than 573°C.

It is possible that a hornfels such as just described might casually be interpreted as a quartz porphyry. Detailed studies, however, show that this interpretation is not compatible with the observed facts. Further studies of the metamorphic rocks of the Cornucopia district indicate that this hornfels may represent a transitional development toward rocks more completely recrystallized.

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[6] Harker, Alfred, *Metamorphism*, Methuen, **1932.**

NOTES AND NEWS

A NOTE ON AENIGMATITE

Norman L. Bowen, *Geophysical Laboratory, Washington, D. C.*

Aenigmatite, long a well-recognized mineral species, has recently been subjected to much reinvestigation. Examination of the crystal structure by Gossner and Mussgnug,[1] definitely removed the mineral from the amphibole group and suggested a new orientation. The remarkable new occurrences in the Chibina-Tundra, Russia, spurred further investigation both chemical and crystallographic,[2] and Palache has made an extended study of the morphology in the light of the orientation suggested by the lattice structure results.[3] Finally Fleischer has given us an interpretative chemical study, using the concept of atomic substitutions in the lattice, and suggests the formula $X_4Y_{13}(Si_2O_7)_6$, which gives $Na_4Fe_9''Fe_2'''Ti_2(Si_2O_7)_6$ as a special case, a composition approached by several examples.[4]

In spite of all this new work no advance appears to have been made in our knowledge of the optical properties. The first quantitative measure of refractive indices was made by Larsen, who records it in his 1921 bulletin among the new data. There only the value of α (1.80±.01) is given and it is stated that the birefringence is rather low. (Specimen from Naujakasik, Greenland.)[5] The birefringence had indeed been previously recorded and was given by Rosenbusch as small, measured with the Babinet compensator $\gamma-\alpha=0.0064$.[6] As now recorded in tables of the optical properties of minerals the entry for aenigmatite appears: $\beta=1.80$ and birefringence 0.006, together with values for extinction angles and other properties long known from work upon thin sections of rocks and oriented plates. Very recently Kunitz has measured the refractive indices of aenigmatite from Pantelleria and gives $\gamma=1.799$ and $\alpha=1.795$, without mentioning the method of measurement.[7] He thus agrees with the older determinations indicating a low value of the birefringence.

In working over some rocks collected by me in East Africa, in many of which aenigmatite (cossyrite) occurs both as small phenocrysts and as minute prisms in the groundmass, I noted that the minutest prisms showed bright between crossed nicols. This is hardly to be expected in a mineral of low birefringence and a measurement of the refractive indices was accordingly undertaken. For this purpose it was necessary to use the phenocrysts, a few of which were picked out of a pantelleritic lava from Lake Niavasha, powdered, and the indices determined by the method of matching in immersion media. No great accuracy is obtainable in a mineral with such strong absorption. The results in sodium light are as follows: $\alpha=1.81\pm.01$ (in substantial agreement with Larsen), $\beta=1.82\pm.01$ and $\gamma=1.88\pm.015$.[8] The optic axial angle 2V is therefore small and positive, a relation generally accepted for aenigmatite. The maximum extinction angle in the zone of the cleavages is 38° and the pleochroism very strong, α = yellow brown, β = brown, γ = deep brown to black.

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[1] Gossner, B., and Mussgnug, F., *Centralbl. Min.*, p. 5, **1929A.**

[2] Kostyleva, E., *Neues Jahrb.*, **1931,** *Band* 1, p. 350 (abstract).

[3] Palache, C., *Zeit. Krist.*, vol. **86,** p. 283, 1933.

[4] Fleischer, Michael, *Am. Jour. Sci.*, vol. **32,** p. 343, 1936.

[5] Larsen, E. S., *U. S. Geol. Survey, Bull.* **679,** p. 71, 1921.

[6] Rosenbusch, H., *Mik. Phys.*, **I,** 2, p. 383, 1905.

[7] Kunitz, W., *Neues Jahrb., Beil. Band* **70,** A 1936, p. 399.

The refractive indices of three other aenigmatites were measured, one from Pantelleria, one from Kangerdluarsuk, Greenland, and one from Chibina-Tundra, all obtained from the U. S. National Museum through the kindess of Dr. Foshag. Although there is considerable variation of composition, the same values of the refractive indices, within the large limits of error stated, seem to suit all of them.

Aenigmatite is thus a mineral of high rather than low birefringence.

NOTES ON MINERALIZATION AT CRESTMORE, CALIFORNIA

Vincent C. Kelley, *California Institute of Technology.*

Recently, in connection with short field trips to the Crestmore quarries several interesting specimens have been collected which reveal some phases of mineralization heretofore unrecorded.

On one trip a large sample of sulphide ore in contact with coarse grained marble was obtained, which came from recent underground workings of the Riverside Cement Company. The sulphide mass is fine grained and bronze-brown in color. It is slightly banded parallel to the marble contact and bedding, suggesting replacement of the marble. Several sections of the sulphides were polished and examined in reflected light. Such study revealed the banding to be due to segregations into blebby stringers and layers of pyrrhotite and chalcopyrite in sphalerite, the last mineral forming the continuous matrix. A few cross veinlets of chalcopyrite cut the other two sulphides. Likewise there is evidence that the sphalerite replaced the pyrrhotite. Also scattered sparingly through the mass are small lenses of hard sulphide. These were found to consist of centers of

[8] The absorption of γ for yellow light is very great. In red light the mineral does not approach opacity so closely for that ray and conviction of the high value of γ is somewhat more readily reached by using red light.

löllingite surrounded and replaced by arsenopyrite which maintains diamond shaped outlines against the matrix of softer sulphides. This is the first mention of löllingite from Crestmore. The genetic sequence thus established for these minerals is: löllingite, arsenopyrite, pyrrhotite, sphalerite, and chalcopyrite.

During the same visits to Crestmore numerous miarolitic cavities were collected from along the north end of the bold face in the Commercial rock quarry. The cavities are irregular and sharply angular in outline, resembling true contraction structures. They exist along a shattered contact between an offshoot of the quartz monzonite porphyry and blue limestone and garnet rock. The rock in which the cavities occur is coarse grained and composed of microcline, quartz, epidote, and brown garnet. The cavities are as much as eight or ten inches in diameter. Microcline, which is the principal mineral, forms stout crystals up to one inch in length. Less abundant are glassy quartz and green epidote crystals ranging up to nearly an inch in length. Both epidote and garnet in numerous small crystals approaching a druse, coat the microcline in many of the cavities.

Euhedral idocrase is well known in the contact rock associated with blue calcite and diopside. Little has been recorded as to the size of these crystals and most of them are under one or two inches in diameter. Recently the writer obtained a nearly complete idocrase crystal made up dominantly of first and second order unit dipyramids with a horizontal diameter of nearly six inches, and a vertical dimension of three inches.

Several specimens have been collected of idocrase and diopside contact-rock which are cut by veins of sky-blue calcite exactly like that of the sky-blue limestone. Eakle[1] suggested the color of the latter was due to carbonaceous material but Daly[2] noted that although occasional graphite flakes were present, the color was not related to the bedding but was sporadic and more intense near the quartz monzonite dikes. This together with its occurrence in primary veins seems to indicate coloration by magmatic introductions into the limestones rather than by substances already present.

Balch Graduate School of the Geological Sciences
California Institute of Technology
Pasadena, California.
Contribution No. 217

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[1] Eakle, A. S., Minerals associated with crystalline limestone at Crestmore, Calif.: *Bull. Dept. of Geol., Univ. of Calif. Pub.*, vol. **10**, p. 343, 1917.

[2] Daly, J. W., A masters thesis presented to the California Institute of Technology, 1931.

AN IMPROVED VANDERWILT ROCK SAW

G. D. Emigh, *University of Arizona, Tucson, Arizona.*

In the October, 1936, issue of the Journal the writer described a simple and inexpensive rock saw. Its construction followed in the main the design of Vanderwilt which was described earlier in this Journal.[1] The writer's design shows some modifications which have resulted in an increased rate of cutting. After his article was written but before it was published, Vanderwilt suggested an additional improvement which resulted in the removal of a difficulty which at times interfered with the successful operation of the saw, i.e., "flopping" of the saw blade. This improvement consists of a wooden bar about 6 feet long attached to a pivot on a cross piece between the right hand legs of the table. Two wires carrying at their lower ends small link chains extend from each end of the saw blade to the wooden bar. By varying the length of the chains the saw blade is kept horizontal. This improvement was described in a footnote on page 674 of the writer's article, but was not shown in the photograph of the apparatus (Fig. 1, p. 670).

Since the article was submitted for publication this improvement has been installed on the Vanderwilt saw at the University of Arizona and has given great satisfaction. The accompanying detail drawings (Figs. 1 and 2) show this improvement and supply all the information necessary for the construction of the rock saw.

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[1] Vanderwilt, John W., A rock saw: *Am. Mineral.*, vol. **19**, pp. 224–229, 1934.

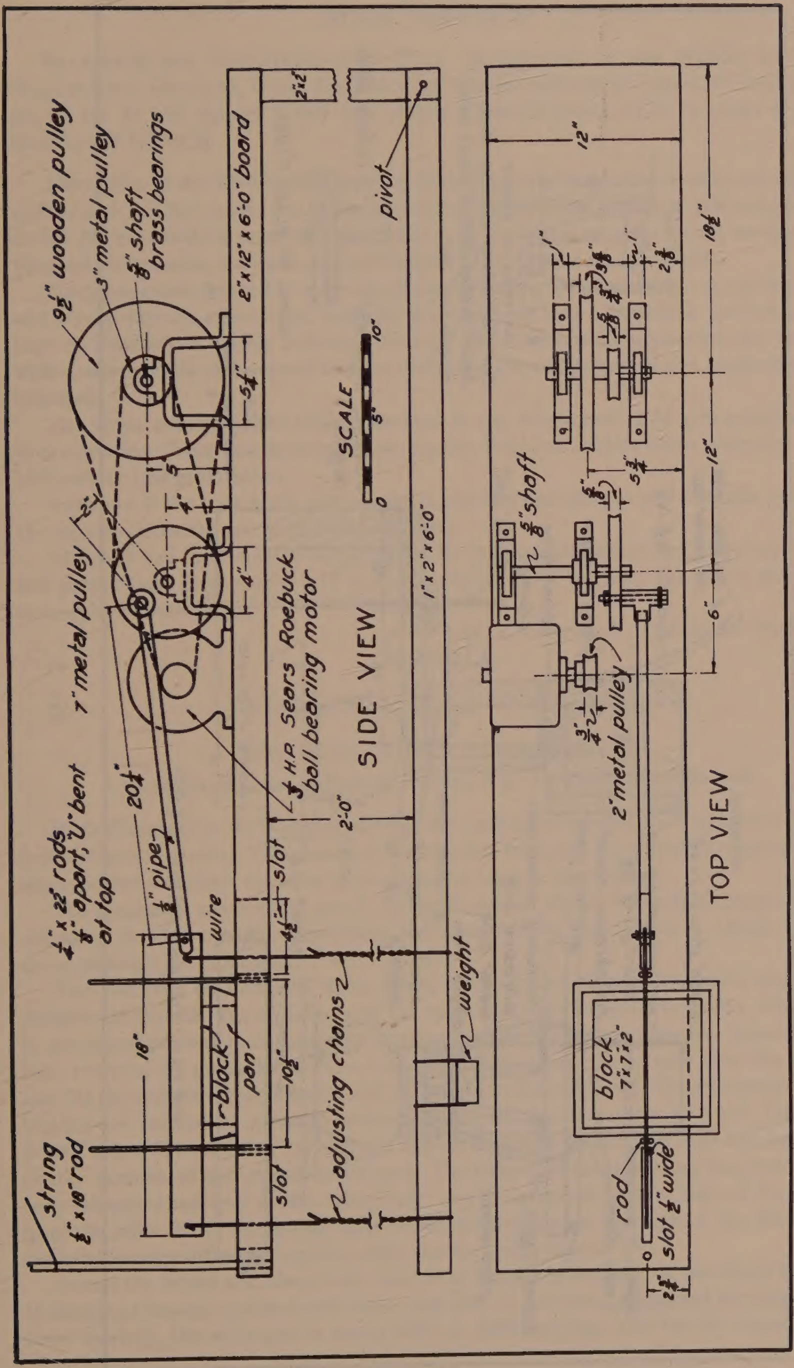
9½" wooden pulley
3" metal pulley
⅝" shaft
brass bearings
2"x12"x6'-0" board
2x2
pivot
SCALE
0
5"
10"
1"x2"x6'-0"
SIDE VIEW
¼ H.P. Sears Roebuck
ball bearing motor
7" metal pulley
2'-0"
20¼"
¼"x22" rods
⅛" apart, 'U' bent
at top
½" pipe
wire
slot
4½"
18"
block
pan
10½"
adjusting chains
weight
string
⅛"x18" rod
slot
5¼"
4"
12"
18½"
⅝" shaft
6"
2" metal pulley
TOP VIEW
block
7x7x2"
rod
slot ½" wide
2¾"

Fig. 1

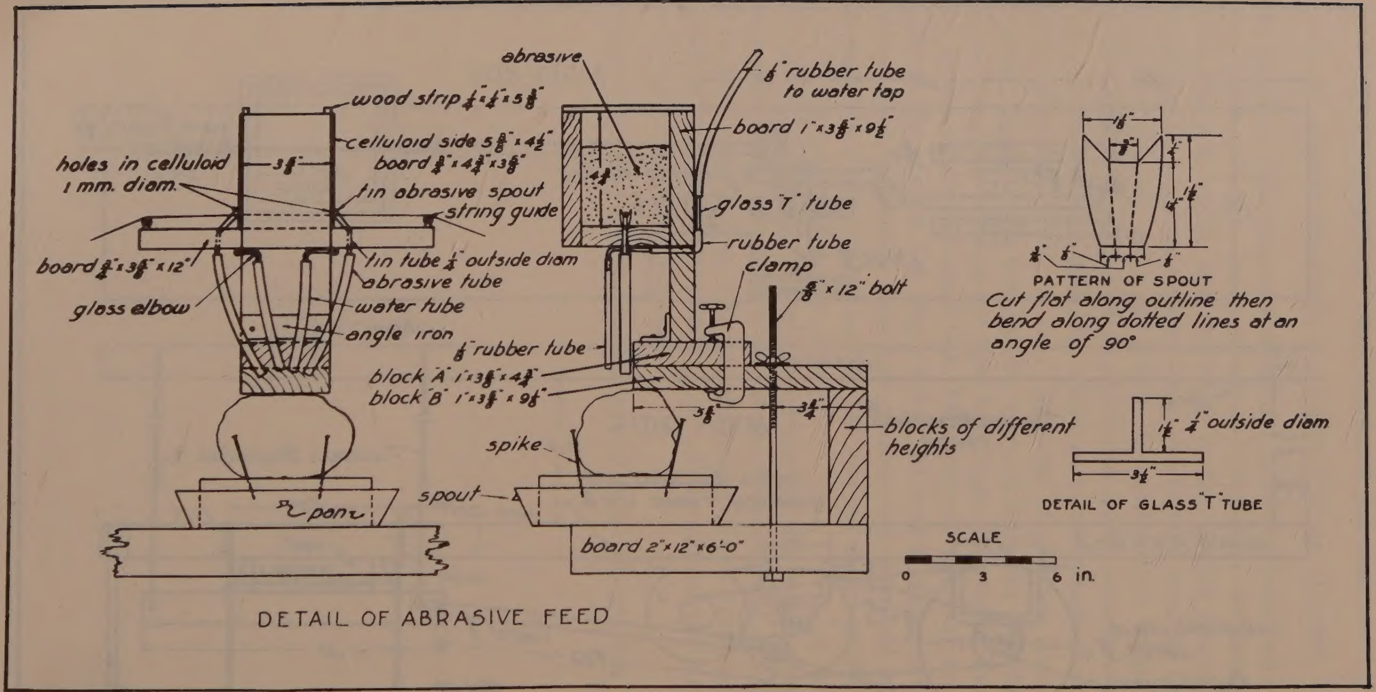
abrasive
wood strip 1/4"×1/4"×5 5/8"
celluloid side 5 5/8"×4 1/2"
board 3/4"×4 3/4"×3 5/8"
holes in celluloid
1 mm. diam.
3 5/8"
tin abrasive spout
string guide
board 3/4"×3 5/8"×12"
tin tube 1/4" outside diam
abrasive tube
glass elbow
water tube
angle iron
1/8" rubber tube
block "A" 1"×3 5/8"×4 3/4"
block "B" 1"×3 5/8"×9 1/8"
spike
spout
pan
4 1/2
1/8" rubber tube
to water tap
board 1"×3 5/8"×9 1/2"
glass "T" tube
rubber tube
clamp
5/8"×12" bolt
3 5/8"
3 3/4"
blocks of different
heights
board 2"×12"×6'-0"
1 1/8"
3/8"
1/4"
1 1/4"
1 1/2"
3/8"
1/8"
1/8"
PATTERN OF SPOUT
Cut flat along outline then
bend along dotted lines at an
angle of 90°
1 1/2"
1/4" outside diam
3 1/2"
DETAIL OF GLASS "T" TUBE
SCALE
0
3
6 in.
DETAIL OF ABRASIVE FEED

FIG. 2

BOOK REVIEW

Praktikum der Edelsteinkunde. Eine Einführung in das Wissen von den Edelsteinen. Georg O. Wild, Franckh'sche Verlagshandlung, Stuttgart, Germany. 133 pp.+4 pp. 44 text figures, 6 half tone plates, 4 colored plates. Price, in paper 6 RM.; linen bound 8.60 RM.

The author of this little book is not only Director of the Institut für Edelsteinforschung at Idar a. d. N., but is also one of the prominent lapidists and dealers of this famous gem center. He is, therefore, unusually well fitted to write a book on gems for the jeweler, and the result is a concise, readable, and yet authoritative treatise on this subject.

Forty pages are devoted to a concise presentation of crystallography, crystal-structure and crystal-physics, clearly and logically developed, so that a beginning student should have no difficulty in readily following the text. The diagrams accompanying this section, while unfortunately rather small in some instances, are well presented and supplement the text well.

The larger portion of the book is devoted to the description of 34 gem minerals and their varieties. These descriptions are necessarily brief but include items generally available only to Idar gem dealers.

A feature of the book is the four colored plates of rough and cut gem minerals, in which the reproductions are extraordinarily well done.

Although this book is intended primarily for jewelers and gem-lovers, the mineralogist and professional gemmologist will find not only much of interest, but also a somewhat new style of presentation.

W. F. Foshag, *U. S. National Museum*

PROCEEDINGS OF SOCIETIES

NEW YORK MINERALOGICAL CLUB

American Museum of Natural History, New York City, Dec. 16, 1936

With President B. T. Butler presiding, the meeting was called to order with 54 members and guests present. The success of the Election Day field trip to the Paterson quarries was reported and plans made for more extensive trips in the Spring.

The speaker of the evening was E. P. Henderson, of the U. S. National Museum, who addressed the club upon his experiences last summer collecting epidote in Alaska. He was accompanied by A. Montgomery and E. Over.

Two localities on Prince of Wales Island were worked, Copper Mountain and Green Monster Mountain. The occurrence of the epidote at both localities is similar, where it is in seams and pockets in an andradite contact rock, formed where Mesozoic limestone has been intruded by granodiorite. The seams of epidote appear to be later than the garnet, and the ore minerals, molybdenite and chalcopyrite, are still later. The crystals from this locality are marked by a domal-prismatic habit and are frequently twinned. Trenching nearby revealed a pocket of crystals of a slightly different habit, quite large and unetched, doubly terminated and mostly untwinned. The Copper Mountain Mine has been practically exhausted and only the old "glory hole" and a few tunnels remain. Some of the epidote from the mine shows interesting light brown terminations at the ends of the deep green crystals. Some zeolites and very few other minerals were found.

Across the Island and about four miles from Copper Mountain, is the Green Monster Mountain, a locality reached with some difficulty. It has been prospected for copper, but never worked. The mountain is about 2900 to 3000 feet high and heavily covered with brush. Trenching was necessary to discover the contact zone between the granodiorite and the limestone. The contact rock was then explored and epidote seams were followed until they widened out into crystal lined druses. Epidote of a different, more tabular habit was collected here. Adularia, calcite and quartz were also found in minor quantities. Quartz is surprisingly rare, but a number of small Japanese twins were collected. Much of the quartz contained inclusions of thin green hairs. Uralite and limonite after pyrite pseudomorphs were collected at this locality. The talk was well-illustrated with lantern slides prepared from Mr. Montgomery's photographs.

At the close of the talk, Mr. James F. Morton of the Paterson Museum announced the discovery of yellow to greenish films of greenockite on gray dolomite from the dump of the old Buckwheat Mine, at Franklin, N. J. The dump is now being removed to fill in stopes, and much old material is being uncovered.

Mr. L. N. Yedlin reported on a trip to the vicinity of Spruce Pine and showed fine specimens of blue hyalite and samarskite from the Glen Mine; torbernite from the dump of the Pine Mountain Mine, and good thulite in crystals and crystalline masses from the Putnam Mine.

Frederick H. Pough
Secretary

While this issue was in press, the sad news was received of the sudden death of Dr. Alexander H. Phillips, former Chairman of the Department of Geology, Princeton University, on Jan. 20, 1937, at the age of 70 years. He was a member of the Princeton faculty for 47 years.

Professor Phillips was one of the Charter Fellows and served The Mineralogical Society of America in various capacities: as a member of the Council 1920–1924; as Treasurer 1924–1929; and as President in 1931.

A memorial will be published at a later date.